

## THE CO-TO-H<sub>2</sub> CONVERSION FACTOR AND DUST-TO-GAS RATIO ON KILOPARSEC SCALES IN NEARBY GALAXIES

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### ABSTRACT

We present maps of the CO-to-H<sub>2</sub> conversion factor ( $\alpha_{\text{CO}}$ ) and dust-to-gas ratio (DGR) in 26 nearby, star-forming galaxies with  $\sim$ kiloparsec spatial resolution. We have simultaneously solved for  $\alpha_{\text{CO}}$  and DGR by assuming that the DGR is approximately constant on kpc scales. With this assumption, we can combine maps of dust mass surface density, CO integrated intensity and HI column density to solve for both  $\alpha_{\text{CO}}$  and DGR with no assumptions about their value or dependence on metallicity or other parameters. Such a study has just become possible with the availability of high resolution far-IR maps from the *Herschel* key program KINGFISH, <sup>12</sup>CO J=(2–1) maps from the IRAM 30m large program HERACLES and HI 21-cm line maps from THINGS. We use a fixed ratio between the (2–1) and (1–0) lines to present our  $\alpha_{\text{CO}}$  results on the more typically used <sup>12</sup>CO J=(1–0) scale and show using literature measurements that variations in the line ratio do not effect our results. In total, we derive 782 individual solutions for  $\alpha_{\text{CO}}$  and DGR. On average,  $\alpha_{\text{CO}} = 3.1 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  for our sample with a standard deviation of 0.3 dex. Within galaxies we observe a generally flat profile of  $\alpha_{\text{CO}}$  as a function of galactocentric radius. However, most galaxies exhibit a lower  $\alpha_{\text{CO}}$  in the central kiloparsec—a factor of  $\sim 2$  below the galaxy mean, on average. In some cases, the central  $\alpha_{\text{CO}}$  value can be factors of 5 to 10 below the standard MW value of  $\alpha_{\text{CO,MW}} = 4.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ . While for  $\alpha_{\text{CO}}$  we find only weak correlations with metallicity, DGR is well-correlated with metallicity, with an approximately linear slope. Finally, we present several recommendations for choosing an appropriate  $\alpha_{\text{CO}}$  for studies of nearby galaxies.

**Keywords:** dust, extinction — infrared: ISM — ISM: ISM — molecules: Galaxies — ISM

## 1. INTRODUCTION

The  $\text{H}_2$  molecule is difficult to observe in the prevalent interstellar medium (ISM) conditions of a normal star-forming galaxy. Since it is the primary constituent of molecular gas, inferring the mass of  $\text{H}_2$  is crucial for studying this phase of the ISM and the star formation that occurs within it. The widespread practice is to use the second most abundant molecule, carbon monoxide ( $^{12}\text{CO}$ ), as a tracer and convert measured CO integrated intensities into  $\text{H}_2$  column densities using a “CO-to- $\text{H}_2$ ” conversion factor  $X_{\text{CO}}$ <sup>1</sup>:

$$N_{\text{H}_2} = X_{\text{CO}} I_{\text{CO}}. \quad (1)$$

In mass surface density units this equation can be rewritten as

$$\Sigma_{\text{H}_2} = \alpha_{\text{CO}} I_{\text{CO}} \quad (2)$$

where  $\Sigma_{\text{H}_2}$  is the total mass surface density of molecular gas (including a correction for the second most abundant element, He). A variety of observations have shown that  $\alpha_{\text{CO}} \approx 4.4 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  is characteristic of the local area of the Milky Way (Solomon et al. 1987; Strong & Mattox 1996; Abdo et al. 2010). Despite uncertainties in the physics behind the conversion factor, the observability of CO ensures that it will remain a widely-used molecular gas tracer, particularly at high redshift. For this reason, measurements of  $\alpha_{\text{CO}}$  in nearby galaxies, where we can relate its variations to local environmental conditions, are critical.

In order to measure the conversion factor, one must measure  $\Sigma_{\text{H}_2}$  (or equivalently,  $\Sigma_{\text{gas}} - \Sigma_{\text{HI}}$ ) independently of CO and then compare it to observed CO integrated intensities. This has been done using a variety of techniques, including: measuring total gas masses from  $\gamma$ -ray emission plus a model for the cosmic ray distribution (Strong & Mattox 1996; Abdo et al. 2010), using the observed velocity dispersion and size of the molecular cloud to obtain virial masses (Solomon et al. 1987; Wilson 1995; Bolatto et al. 2008; Donovan Meyer et al. 2012; Wei et al. 2012; Gratier et al. 2012), and modeling multiple molecular gas lines with varying optical depths and critical densities (e.g. Weiß et al. 2001; Israel 2009b,a). In general, few of these techniques are effective for constraining  $\alpha_{\text{CO}}$  in galaxies outside the Local Group due to the difficulty of obtaining the necessary observations (e.g.  $\gamma$ -ray maps or CO mapping at  $< 100 \text{ pc}$  resolution) or doubts about fundamental assumptions (e.g. that CO traces the full extent of molecular gas in the clouds; that the clouds lack contributions to virial balance from magnetic or pressure forces; that simple radiative transfer models can reproduce molecular gas excitation on kpc-scales).

Another potential technique to measure  $\Sigma_{\text{H}_2}$  is to use dust as a tracer of total gas column. Assuming that dust and gas are well mixed, the dust-to-gas ratio (DGR) is not a function of atomic/molecular phase and the fraction of mass in ionized gas is negligible, the observed dust mass surface density can be converted to a gas mass sur-

face density with information on the DGR, i.e. using the following equation:

$$\frac{\Sigma_{\text{D}}}{\text{DGR}} = \Sigma_{\text{HI}} + \Sigma_{\text{H}_2} = \Sigma_{\text{HI}} + \alpha_{\text{CO}} I_{\text{CO}}. \quad (3)$$

Here  $\Sigma_{\text{D}}$  is the mass surface density of dust and  $\Sigma_{\text{HI}}$  and  $\Sigma_{\text{H}_2}$  are the mass surface densities of atomic and molecular gas<sup>2</sup>, respectively, and DGR is the dust-to-gas mass ratio. By measuring  $\Sigma_{\text{D}}$  and  $\Sigma_{\text{HI}}$  and assuming the DGR (or simultaneously measuring it, as we will discuss shortly), the molecular gas mass can be determined. While still subject to its own systematic uncertainties, this technique relies on a different set of assumptions than those mentioned previously.

Studies of DGR or  $\alpha_{\text{CO}}$  have typically fixed one of the parameters in order to determine the other, so it is difficult to avoid circularity when using a fixed DGR to solve for  $\alpha_{\text{CO}}$  in Equation 3. Alternatively, with sufficiently high spatial resolution, DGR can be determined on sight-lines free of molecular gas and extrapolated to regions where CO is detected. For very nearby galaxies like the Magellanic Clouds, such a technique has been used by Israel (1997) and Leroy et al. (2009b), who found that  $\alpha_{\text{CO}}$  determinations from virial masses can be strongly biased by envelopes of “CO-dark” molecular gas in low-metallicity systems. In more distant galaxies, we generally cannot isolate purely atomic lines of sight at the resolution of typical HI and CO observations. Instead, it is possible to use a technique developed by Leroy et al. (2011) to simultaneously measure  $\alpha_{\text{CO}}$  and DGR using the assumption that DGR should be constant over a region of a galaxy. Since we can now achieve  $\sim \text{kpc}$  spatial resolution in the far-IR with *Herschel* and have sensitive, high-resolution CO and HI maps, it is possible to extend this technique, which has thus far only been applied to the Local Group, to more distant galaxies.

The idea behind this technique (explained in detail in Section 3) is that spatially resolved measurements of  $\Sigma_{\text{D}}$ ,  $\Sigma_{\text{HI}}$  and  $I_{\text{CO}}$  allow one to solve for  $\alpha_{\text{CO}}$  and DGR in a region when it is smaller than the typical scale over which DGR varies (i.e. it is well represented by one DGR value) and it covers a range of CO/HI ratios. Having chosen an appropriately sized region, we can determine these two constants, defining the best fit as that which produces the most uniform DGR for the multiple lines-of-sight included in the region. This technique assumes no prior value of DGR or  $\alpha_{\text{CO}}$ —it makes use of the (by definition) linear dependence of  $\Sigma_{\text{H}_2}$  on  $\alpha_{\text{CO}}$  to identify the solution. The technique is therefore only applicable in regions where CO is detected. Constraining  $\alpha_{\text{CO}}$  in more extreme conditions would require different techniques (see Schruba et al. 2012, for more discussion).

One useful aspect of solving simultaneously for  $\alpha_{\text{CO}}$  and DGR is that the absolute normalization of the dust tracer is irrelevant for the determination of  $\alpha_{\text{CO}}$  as long as it is linear with the “true”  $\Sigma_{\text{D}}$ . Since the DGR is calibrated from the map itself, any constant term will show up in both DGR and  $\Sigma_{\text{D}}$  and makes no impact on the assessment of  $\Sigma_{\text{H}_2}$ . For example, Leroy et al. (2011) showed

<sup>1</sup> We refer to the CO-to- $\text{H}_2$  conversion factor in mass units throughout this paper. Including a factor of 1.36 for helium,  $X_{\text{CO}} = 2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$  corresponds to  $\alpha_{\text{CO}} = 4.35 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ .  $\alpha_{\text{CO}}$  can be converted to  $X_{\text{CO}}$  units by multiplying by a factor of  $4.6 \times 10^{19}$ .

<sup>2</sup> In converting from column densities to mass surface densities, we account for helium with a factor of 1.36. For  $\Sigma_{\text{H}_2}$ , this factor is included in the  $\alpha_{\text{CO}}$  term. We apply the helium correction to  $\Sigma_{\text{HI}}$  as well.

that the dust optical depth at  $160\ \mu\text{m}$ , determined using an assumed power-law dependence on frequency and an estimate of the dust temperature from the  $70/160$  ratio, works comparably well as the dust mass surface density. Dobashi et al. (2008) performed a similar study in the Large Magellanic Cloud using  $A_V$  mapping to trace dust mass surface density. Since we are also interested in the value of DGR itself, we use  $\Sigma_D$  as our tracer throughout this paper. We note that uncertainties in the absolute value of  $\Sigma_D$ , as long as they do not introduce a non-linearity within the region in question, will not affect the determination of  $\alpha_{\text{CO}}$ .

For this study, we make use of CO  $J=(2-1)$  observations from the large program HERACLES on the IRAM 30m (Leroy et al. 2009a). It is important to note that we are therefore determining  $\alpha_{\text{CO}}$  appropriate for that CO line. Since most studies quote  $\alpha_{\text{CO}}$  for the CO  $J=(1-0)$  line, throughout the paper we use a line ratio ( $R_{21}$ ) to convert our measurements to the  $(1-0)$  scale. Systematic variations in  $R_{21}$  will result in errors in the  $(1-0)$  conversion factor, but the  $(2-1)$  conversion factor will not be affected since it is what we are directly deriving. Although it is convenient to discuss  $\alpha_{\text{CO}}$  in its typical  $(1-0)$  incarnation, we note that the  $(2-1)$  conversion factor itself will be important for future studies with ALMA. For nearby galaxies, at a given angular resolution, mapping in the  $(2-1)$  line is more efficient than in the  $(1-0)$  line. For high redshift galaxies, the  $(1-0)$  line may be shifted out of ALMA’s frequency coverage. Thus,  $\alpha_{\text{CO}}$  for the  $(2-1)$  line will be useful regardless of its relationship to  $(1-0)$ .

This paper is laid out as follows: Section 2 presents the details of the resolved dust and gas observations we use. In Section 3 we describe the technique to simultaneously measure DGR and  $\alpha_{\text{CO}}$  and discuss how the procedure is optimized to deal with more distant galaxies than those in the Local Group (more details on the technique can be found in the Appendix). We present the results of performing the solution on 26 nearby galaxies in Section 4 and discuss their implications for our understanding of how DGR and  $\alpha_{\text{CO}}$  vary with metallicity and other ISM properties in Section 6.

## 2. OBSERVATIONS

We make use of observations of dust and gas from a series of surveys of nearby galaxies built upon SINGS (the “Spitzer Infrared Nearby Galaxies Survey”; Kennicutt et al. 2003). This includes HI from “The HI Nearby Galaxies Survey” (THINGS; Walter et al. 2008),  $^{12}\text{CO}$   $J=(2-1)$  from the “HERA CO Line Emission Survey” (HERACLES; Leroy et al. 2009a, Leroy et. al, in prep) and far-infrared dust emission from “Key Insights into Nearby Galaxies: A Far-Infrared Survey with Herschel” (KINGFISH; Kennicutt et al. 2011). In addition, several galaxies that were not included in THINGS have HI observations from either archival or new observations. The sample of galaxies in common between these surveys and for which we have detections of CO emission (see Schruba et al. 2012, for details on the HERACLES non-detections) consists of 26 targets listed in Table 1.

The SINGS and KINGFISH surveys targeted galaxies with a variety of morphologies, located within 30 Mpc. Due to the requirement of a CO detection for our work, all but one of the viable targets are spiral galaxies, the

exception being NGC 3077 which is a starbursting dwarf. In Table 1 we list the positions, distances, orientation parameters and the B-band isophotal radii at 25 mag  $\text{arcsec}^{-2}$  ( $R_{25}$ ) for our targets. Throughout the text we define  $r_{25} = r/R_{25}$ , where  $r$  is the galactocentric radius in units of arcminutes.

### 2.1. Dust Mass Surface Density

We use dust mass surface density maps derived from pixel-by-pixel modeling of the infrared (IR) spectral energy distribution (SED) observed by *Spitzer* and *Herschel* with models developed by Draine & Li (2007). A detailed description of the modeling for NGC 0628 and NGC 6946 is presented in Aniano et al. (2012) and the full sample results are presented in Aniano et al (in prep). The dust models include a description of the dust properties (size distribution, composition and optical properties of the grains) with a variable fraction of dust in the form of polycyclic aromatic hydrocarbons (PAHs). The dust is illuminated by a radiation field distribution wherein a fraction of the dust is heated by a minimum radiation field  $U_{\text{min}}$  while the rest is heated by a power-law distribution of radiation fields extending up to  $U=10^7 U_{\text{MMP}}$ , where  $U_{\text{MMP}}$  is the solar neighborhood radiation field from Mathis et al. (1983). The fraction of the dust mass heated by radiation fields where  $U>10^2 U_{\text{MMP}}$  is typically very small, so the dust mass surface density is not very sensitive to the exact value of the upper  $U$  limit.

The resolution of the dust mass surface density map is equivalent to that of the lowest resolution IR map included in the modeling. In order to preserve spatial resolution while still covering the peak of the dust SED, we use the dust modeling at a resolution matched to the SPIRE 350  $\mu\text{m}$  map (FWHM  $\sim 25''$ ). This limiting resolution allows us to include the following maps in the dust modeling: IRAC 3.6, 4.5, 5.8 and 8.0  $\mu\text{m}$ ; MIPS 24 and 70  $\mu\text{m}$ ; PACS 70, 100 and 160  $\mu\text{m}$ ; and SPIRE 250 and 350  $\mu\text{m}$ . In theory, we could perform this analysis at even higher resolution using the SPIRE 250 resolution maps, which include all IRAC bands; MIPS 24  $\mu\text{m}$ ; all PACS bands; and SPIRE 250  $\mu\text{m}$ . However, Aniano et al. (2012) found that maps where the limiting resolution exceeds MIPS 70  $\mu\text{m}$  are less reliable due to the comparatively low surface brightness sensitivity of the PACS observations. At SPIRE 250  $\mu\text{m}$  resolution, they find systematic errors of up to  $\sim 30-40\%$  in the dust mass (compared to their best estimate, which includes all IRAC, MIPS, PACS and SPIRE bands). However, when both SPIRE 250 and 350 observations are included, the systematic errors in the dust mass are  $\sim 10\%$  or less. We proceed by using the SPIRE 350 resolution dust modeling results.

Aside from the dust mass surface density, the Aniano et al. (2012) modeling also constrains a number of other quantities that we make use of later in interpreting the results. These include  $\bar{U}$ , the average radiation field heating the dust;  $U_{\text{min}}$  the minimum radiation field;  $f_{\text{PDR}}$  the fraction of the dust luminosity that comes from dust heated by  $U > 100 U_{\text{MMP}}$ ; and  $q_{\text{PAH}}$  the fraction of the dust mass accounted for by PAHs with fewer than  $10^3$  carbon atoms.

Statistical uncertainties on  $\Sigma_D$  and the other derived parameters were measured by Aniano et al. (2012) with

**Table 1**  
Galaxy Sample

Galaxy	R.A. (J2000)	Dec. (J2000)	Distance (Mpc)	$i$ ( $^{\circ}$ )	P.A. ( $^{\circ}$ )	Morphology	$R_{25}$ ( $''$ )	Solution Pixel <sup>a</sup> Radius (kpc)
NGC 0337	00 <sup>h</sup> 59 <sup>m</sup> 50 <sup>s</sup> .1	−07°34′41″.0	19.3	51	90	SBd	1.5	3.5
NGC 0628	01 <sup>h</sup> 36 <sup>m</sup> 41 <sup>s</sup> .8	+15°47′00″.0	7.2	7	20	SAC	4.9	1.3
NGC 0925	02 <sup>h</sup> 27 <sup>m</sup> 16 <sup>s</sup> .5	+33°34′43″.5	9.1	66	287	SABd	5.4	1.7
NGC 2841	09 <sup>h</sup> 22 <sup>m</sup> 02 <sup>s</sup> .6	+50°58′35″.2	14.1	74	153	SAb	3.5	2.6
NGC 2976	09 <sup>h</sup> 47 <sup>m</sup> 15 <sup>s</sup> .3	+67°55′00″.0	3.6	65	335	SAC	3.6	0.6
NGC 3077	10 <sup>h</sup> 03 <sup>m</sup> 19 <sup>s</sup> .1	+68°44′02″.0	3.8	46	45	IOpec	2.7	0.7
NGC 3184 <sup>*</sup>	10 <sup>h</sup> 18 <sup>m</sup> 17 <sup>s</sup> .0	+41°25′28″.0	11.7	16	179	SABcd	3.7	2.1
NGC 3198	10 <sup>h</sup> 19 <sup>m</sup> 55 <sup>s</sup> .0	+45°32′58″.9	14.1	72	215	SBc	3.2	2.6
NGC 3351 <sup>*</sup>	10 <sup>h</sup> 43 <sup>m</sup> 57 <sup>s</sup> .7	+11°42′14″.0	9.3	41	192	SBb	3.6	1.7
NGC 3521 <sup>*</sup>	11 <sup>h</sup> 05 <sup>m</sup> 48 <sup>s</sup> .6	−00°02′09″.2	11.2	73	340	SABbc	4.2	2.0
NGC 3627 <sup>*</sup>	11 <sup>h</sup> 20 <sup>m</sup> 15 <sup>s</sup> .0	+12°59′29″.6	9.4	62	173	SABb	5.1	1.7
NGC 3938	11 <sup>h</sup> 52 <sup>m</sup> 49 <sup>s</sup> .4	+44°07′14″.9	17.9	14	195	SAC	1.8	3.3
NGC 4236	12 <sup>h</sup> 16 <sup>m</sup> 42 <sup>s</sup> .1	+69°27′45″.0	4.5	75	162	SBdm	12.0	0.8
NGC 4254 <sup>*</sup>	12 <sup>h</sup> 18 <sup>m</sup> 49 <sup>s</sup> .6	+14°24′59″.0	14.4	32	55	SAC	2.5	2.6
NGC 4321 <sup>*</sup>	12 <sup>h</sup> 22 <sup>m</sup> 54 <sup>s</sup> .9	+15°49′21″.0	14.3	30	153	SABbc	3.0	2.6
NGC 4536 <sup>*</sup>	12 <sup>h</sup> 34 <sup>m</sup> 27 <sup>s</sup> .1	+02°11′16″.0	14.5	59	299	SABbc	3.5	2.6
NGC 4569 <sup>*</sup>	12 <sup>h</sup> 36 <sup>m</sup> 49 <sup>s</sup> .8	+13°09′46″.0	9.9	66	23	SABab	4.6	1.8
NGC 4625	12 <sup>h</sup> 41 <sup>m</sup> 52 <sup>s</sup> .7	+41°16′26″.0	9.3	47	330	SABmp	0.7	1.7
NGC 4631	12 <sup>h</sup> 42 <sup>m</sup> 08 <sup>s</sup> .0	+32°32′29″.0	7.6	85	86	SBd	7.3	1.4
NGC 4725	12 <sup>h</sup> 50 <sup>m</sup> 26 <sup>s</sup> .6	+25°30′03″.0	11.9	54	36	SABab	4.9	2.2
NGC 4736 <sup>*</sup>	12 <sup>h</sup> 50 <sup>m</sup> 53 <sup>s</sup> .0	+41°07′13″.2	4.7	41	296	SAab	3.9	0.8
NGC 5055 <sup>*</sup>	13 <sup>h</sup> 15 <sup>m</sup> 49 <sup>s</sup> .2	+42°01′45″.3	7.9	59	102	SAbc	5.9	1.4
NGC 5457 <sup>b*</sup>	14 <sup>h</sup> 03 <sup>m</sup> 12 <sup>s</sup> .6	+54°20′57″.0	6.7	18	39	SABcd	12.0	1.2
NGC 5713	14 <sup>h</sup> 40 <sup>m</sup> 11 <sup>s</sup> .5	−00°17′21″.0	21.4	48	11	SABbcp	1.2	3.9
NGC 6946 <sup>*</sup>	20 <sup>h</sup> 34 <sup>m</sup> 52 <sup>s</sup> .2	+60°09′14″.4	6.8	33	243	SABcd	5.7	1.2
NGC 7331	22 <sup>h</sup> 37 <sup>m</sup> 04 <sup>s</sup> .0	+34°24′56″.5	14.5	76	168	SAb	4.6	2.6

**Note.** — Distances and morphologies from the compilation of Kennicutt et al. (2011). Orientation parameters from Walter et al. (2008) where possible, LEDA and NED databases otherwise.

<sup>a</sup> Solution pixels are defined in Section 3. They are the regions in which we solve for  $\alpha_{\text{CO}}$  and DGR.

<sup>b</sup> M101

<sup>\*</sup> CO J= (1 − 0) maps available from Nobeyama survey of nearby galaxies (Kuno et al. 2007).

a Monte Carlo approach. In most of the regions we consider the statistical uncertainties on the dust mass surface densities are small, but the S/N of the dust mass maps is generally a function of radius and the outskirts can have  $S/N \sim 5$  in some cases. Our error estimates take these uncertainties into account and are described in Section 3.3. Potential systematic effects are discussed in Section 3.5.

## 2.2. HI Surface Density

To trace the atomic gas surface density in our targets, we use a combination of NRAO<sup>3</sup> VLA HI observations from THINGS (Walter et al. 2008) and supplementary HI, both new and archival, described in Leroy et al. (in prep.). The source and angular resolution of the HI maps for our targets are listed in Table 2.

The HI maps are converted from integrated intensities to column densities as in Equation 5 of Walter et al. (2008). We convolve each map with an elliptical Gaussian kernel determined by its individual beam properties to produce a circular Gaussian point spread function (PSF). We then use kernels created following the procedures in Aniano et al. (2011) to convolve the circular Gaussian to match the PSF at SPIRE 350  $\mu\text{m}$ . For the HI we assume the uncertainties to be the larger of

**Table 2**  
HI Observation Summary

Galaxy	Source	FWHM Beam Properties		
		Major ( $''$ )	Minor ( $''$ )	P.A. ( $^{\circ}$ )
NGC 0337	Archival	20.2	13.0	160.3
NGC 0628	THINGS	11.9	9.3	−70.3
NGC 0925	THINGS	5.9	5.7	30.6
NGC 2841	THINGS	11.1	9.4	−12.3
NGC 2976	THINGS	7.4	6.4	71.8
NGC 3077	THINGS	14.3	13.2	60.5
NGC 3184	THINGS	7.5	6.9	85.4
NGC 3198	THINGS	11.4	9.4	−80.4
NGC 3351	THINGS	9.9	7.1	24.1
NGC 3521	THINGS	14.1	11.2	−61.7
NGC 3938	Archival	18.5	18.2	48.6
NGC 3627	THINGS	10.0	8.9	−60.9
NGC 4236	New	16.7	13.9	69.6
NGC 4254	Archival	16.9	16.2	54.4
NGC 4321	Archival	14.7	14.1	163.4
NGC 4536	Archival, New	14.7	13.8	−11.4
NGC 4569	Archival	14.2	13.9	32.9
NGC 4625	Archival	13.0	12.5	−29.2
NGC 4631	Archival	14.9	13.3	178.1
NGC 4725	Archival, New	18.6	17.0	−20.9
NGC 4736	THINGS	10.2	9.1	−23.0
NGC 5055	THINGS	10.1	8.7	−40.0
NGC 5457	THINGS	10.8	10.2	−67.1
NGC 5713	Archival	15.5	14.9	121.9
NGC 6946	THINGS	6.0	5.6	6.6
NGC 7331	THINGS	6.1	5.6	34.3

**Note.** — Galaxies with new HI data were observed in VLA project AL735 (P.I. A. Leroy).

<sup>3</sup> The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.



either  $0.5 \text{ M}_{\odot} \text{ pc}^{-2}$  or 10% of the measured column density. Potential systematic uncertainties from HI opacity effects are discussed in Section 3.4.

### 2.3. CO Integrated Intensity

To trace the molecular gas distribution in our targets we use CO  $J=(2-1)$  mapping from the HERACLES survey (Leroy et al. 2009a). Integrated intensity maps were generated from the CO spectral cubes by integrating the spectra over a range in velocity around either 1) the detected CO line in that spectrum or 2) the expected CO velocity predicted from the HI velocity (since HI is detected at high S/N in almost all relevant pixels). We propagate uncertainties through these masking steps, creating in the end an integrated CO line map and an uncertainty map. The HERACLES maps have PSFs well approximated by a circular Gaussian with FWHM of  $13.4''$ . We convolve the maps with kernels constructed using the techniques described by Aniano et al. (2011) to match the resolution of the SPIRE 350 maps. We have tested the effect of error beams (i.e. extended wings of the PSF or stray light pick-up of the IRAM 30-m) on the HERACLES maps and find that the effect is less than  $\sim 5\%$  for all galaxies and closer to 1% for most.

Our measurements of  $\alpha_{\text{CO}}$  directly determine the conversion factor appropriate for CO  $J=(2-1)$ . However, to compare with the standard CO  $J=(1-0)$  factor, which is more frequently used, we convert to  $(1-0)$  using a fixed value of the line ratio  $R_{21}=(2-1)/(1-0) = 0.7$ . Due to revised telescope efficiencies, the  $R_{21}$  we use differs slightly from what was used in Leroy et al. (2009a). The  $R_{21}$  we assume was found to be an appropriate average for the HERACLES sample (E. Rosolowsky, private communication). We discuss the effects of assuming a fixed  $R_{21}$  on our results for the  $(1-0)$  conversion factor in Section 3.4. To apply the  $\alpha_{\text{CO}}$  we report in the following sections to CO  $J=(2-1)$  observations, its value should be divided by 0.7.

## 2.4. Ancillary Datasets

### 2.4.1. Metallicity

In the analysis presented in Section 4 we study the variations of  $\alpha_{\text{CO}}$  and DGR as a function of metallicity. Wherever possible, we make use of the metallicity measurements from Moustakas et al. (2010, hereafter M10) who derived characteristic metallicities as well as radial gradients in oxygen abundance for the SINGS sample. M10 present results using two different calibrations for the strong line abundances—from Kobulnicky & Kewley (2004, KK04) and Pilyugin & Thuan (2005, PT05). Both calibrations are considered in the following analysis.

Our preferred metallicity measurement is a radial gradient from HII region metallicities (M10, Table 8). For several galaxies no radial gradient measurement is available, so we use a fixed metallicity for the entire galaxy equal to the “characteristic metallicity” (M10, Table 9). In the case of NGC 4236 and 4569, the only metallicity measurements available are from the B-band luminosity-metallicity ( $L-Z$ ) relationship and we use those values from M10 with no gradient. Finally, two of our galaxies are not in the M10 sample. For NGC 3077 we use a metallicity of  $12+\log(\text{O}/\text{H})=8.9$  in KK04 with no gradient, from Calzetti et al. (1994). To obtain a PT05 mea-

surement for NGC 3077, we subtract 0.6 dex, the average offset between the two calibrations found by M10. For NGC 5457 (a.k.a. M101), a galaxy with a well-known radial metallicity gradient, we use the measurements from Bresolin (2007). These metallicities are from direct methods, so are not on the same scale as either PT05 or KK04. The metallicities and gradients we use are listed in Table 3. These are converted to match the  $r_{25}$  we adopt in this work, which can be slightly different from that adopted by M10. In order to compare with the local MW, we use the metallicity of the Orion Nebula HII region in the PT05 and KK04 calibrations from work by Croxall et al. (in prep), i.e.  $12+\log(\text{O}/\text{H})=8.5$  for PT05 and 8.8 for KK04.

### 2.4.2. Star Formation Rate and Stellar Mass Surface Density Maps

The star formation rate surface densities ( $\Sigma_{\text{SFR}}$ ) are calculated from H $\alpha$  and  $24 \mu\text{m}$  maps using the H $\alpha$  maps and procedure described in Leroy et al. (2012). The H $\alpha$  maps have been convolved to match the SPIRE 350  $\mu\text{m}$  PSF assuming an initial  $\sim 1-2''$  FWHM Gaussian PSFs, although the large difference between the initial and final PSF makes this choice mostly irrelevant. We use  $24 \mu\text{m}$  maps from SINGS, processed (background subtracted, convolved and aligned) as described in Aniano et al. (2012). The Aniano et al. (2012) modeling results described in Section 2.1 are also used to remove a non-star-formation related cirrus component from the  $24 \mu\text{m}$  map as described in Leroy et al. (2012).

We calculate the stellar mass surface density ( $\Sigma_*$ ) from the IRAC  $3.6 \mu\text{m}$  observations from SINGS, as described in Leroy et al. (2008). This provides only a rough tracer of stellar mass surface density, since we do not take into account corrections for various contaminants in the  $3.6 \mu\text{m}$  band (Zibetti & Groves 2011; Meidt et al. 2012).

## 2.5. Processing

After all maps have been convolved to SPIRE 350  $\mu\text{m}$  resolution, we sample them with a hexagonal grid with approximately half-beam spacings (i.e.  $12.5''$ ). Uncertainties on the dust mass surface density, CO integrated intensity and HI column density are propagated through the necessary convolutions and samplings. Surface densities and other quantities have been deprojected using the orientation parameters listed in Table 1.

## 3. SOLVING SIMULTANEOUSLY FOR $\alpha_{\text{CO}}$ AND DGR

In order to use the dust mass surface density to trace the total gas mass surface density, we assume 1) that dust and gas are well mixed (i.e. that Equation 3 holds), 2) that the DGR is constant on  $\sim\text{kpc}$  scales in our target galaxies and 3) within a given  $\sim\text{kpc}$  region, the DGR does not change between the atomic and molecular phases. Then, given multiple measurements of  $\Sigma_{\text{D}}$ ,  $\Sigma_{\text{HI}}$  and  $\text{I}_{\text{CO}}$  that span a range of CO/HI values in a kpc-scale region of a galaxy, we can adjust  $\alpha_{\text{CO}}$  till we find the value that returns the most uniform DGR for the region. This procedure makes no assumption about the value of the DGR, only that it is constant in that region. In addition, it makes no assumption about the value of  $\alpha_{\text{CO}}$  or the scales on which it varies. If  $\alpha_{\text{CO}}$  varies on small scales, our measured  $\alpha_{\text{CO}}$  value will represent the

**Table 3**  
Adopted Metallicities and Gradients

Galaxy	PT05 Central Metallicity (12 + log(O/H))	PT05 Metallicity Gradient (dex $r_{25}^{-1}$ )	KK04 Central Metallicity (12 + log(O/H))	KK04 Metallicity Gradient (dex $r_{25}^{-1}$ )	Source
NGC 0337	8.18 ± 0.07	...	8.84 ± 0.05	...	M10 Table 9
NGC 0628	8.43 ± 0.02	−0.25 ± 0.05	9.19 ± 0.02	−0.54 ± 0.04	M10 Table 8
NGC 0925	8.32 ± 0.01	−0.21 ± 0.03	8.91 ± 0.01	−0.43 ± 0.02	M10 Table 8
NGC 2841	8.72 ± 0.12	−0.54 ± 0.39	9.34 ± 0.07	−0.36 ± 0.24	M10 Table 8
NGC 2976	8.36 ± 0.06	...	8.98 ± 0.03	...	M10 Table 9
NGC 3077	8.30 ± 0.20	...	8.90 ± 0.20	...	K11
NGC 3184	8.65 ± 0.02	−0.46 ± 0.06	9.30 ± 0.02	−0.52 ± 0.05	M10 Table 8
NGC 3198	8.49 ± 0.04	−0.38 ± 0.11	9.10 ± 0.03	−0.50 ± 0.08	M10 Table 8
NGC 3351	8.69 ± 0.01	−0.27 ± 0.04	9.24 ± 0.01	−0.15 ± 0.03	M10 Table 8
NGC 3521	8.44 ± 0.05	−0.12 ± 0.25	9.20 ± 0.03	−0.52 ± 0.15	M10 Table 8
NGC 3627	8.34 ± 0.24	...	8.99 ± 0.10	...	M10 Table 9
NGC 3938	8.42 ± 0.20	...	9.06 ± 0.20	...	M10 L–Z
NGC 4236	8.17 ± 0.20	...	8.74 ± 0.20	...	M10 L–Z
NGC 4254	8.56 ± 0.02	−0.35 ± 0.08	9.26 ± 0.02	−0.39 ± 0.06	M10 Table 8
NGC 4321	8.61 ± 0.07	−0.31 ± 0.17	9.29 ± 0.04	−0.28 ± 0.11	M10 Table 8
NGC 4536	8.21 ± 0.08	...	9.00 ± 0.04	...	M10 Table 9
NGC 4569	8.58 ± 0.20	...	9.26 ± 0.20	...	M10 L–Z
NGC 4625	8.35 ± 0.17	...	9.05 ± 0.07	...	M10 Table 9
NGC 4631	8.12 ± 0.11	...	8.75 ± 0.09	...	M10 Table 9
NGC 4725	8.35 ± 0.13	...	9.10 ± 0.08	...	M10 Table 9
NGC 4736	8.40 ± 0.01	−0.23 ± 0.12	9.04 ± 0.01	−0.08 ± 0.10	M10 Table 8
NGC 5055	8.59 ± 0.07	−0.59 ± 0.27	9.30 ± 0.04	−0.51 ± 0.17	M10 Table 8
NGC 5457	8.75 ± 0.05	−0.75 ± 0.06	8.75 ± 0.05	−0.75 ± 0.07	B07
NGC 5713	8.48 ± 0.10	...	9.08 ± 0.03	...	M10 Table 9
NGC 6946	8.45 ± 0.06	−0.17 ± 0.15	9.13 ± 0.04	−0.28 ± 0.10	M10 Table 8
NGC 7331	8.41 ± 0.06	−0.21 ± 0.31	9.18 ± 0.05	−0.49 ± 0.25	M10 Table 8

**References.** — Moustakas et al. (2010, M10), Kennicutt et al. (2011, K11), Bresolin (2007, B07).

dust (or gas) mass surface density weighted average  $\alpha_{\text{CO}}$  for the region. We discuss this process in detail in the following sections.

A simultaneous solution for  $\alpha_{\text{CO}}$  and DGR can only be performed if a range of CO/HI ratios are present in the measurements. The linear dependence of  $\Sigma_{\text{H}_2}$  on  $\alpha_{\text{CO}}$  provides leverage to adjust  $\alpha_{\text{CO}}$  in order to best describe all of the points with the same DGR over the range of CO/HI ratios. An “incorrect”  $\alpha_{\text{CO}}$  value will cause a dependence of the measured DGR on CO/HI, increasing the spread in DGR values in the region. An illustration of this effect is shown in panel c) of Figure 1. Finding a solution or best-fit  $\alpha_{\text{CO}}$  is equivalent to locating a minimum in the DGR scatter at a given value of  $\alpha_{\text{CO}}$ .

The basic procedure we use, minimizing the scatter in the DGR values in the region, was suggested in Leroy et al. (2011). There are, however, a variety of other techniques to solve for  $\alpha_{\text{CO}}$  and DGR given multiple measurements, including directly fitting a plane to  $\text{I}_{\text{CO}}$ ,  $\Sigma_{\text{D}}$  and  $\Sigma_{\text{HI}}$ . It is not clear *a priori* which scatter minimization technique is optimal, so we performed a set of simulations, described in the Appendix, to test various techniques and optimize the procedure for our dataset and objectives. We describe the resulting scatter minimization procedure in more detail below.

### 3.1. Defining the “Solution Pixel”

To perform the solution, we require multiple measurements of dust and gas tracers in the region. We also aim, however, to select the smallest possible regions, in order to ensure an approximately constant DGR. We proceed by dividing each target galaxy into hexagonal regions encompassing 37 of the half-beam spaced sampling points. We call these regions “solution pixels” (see panel a) of

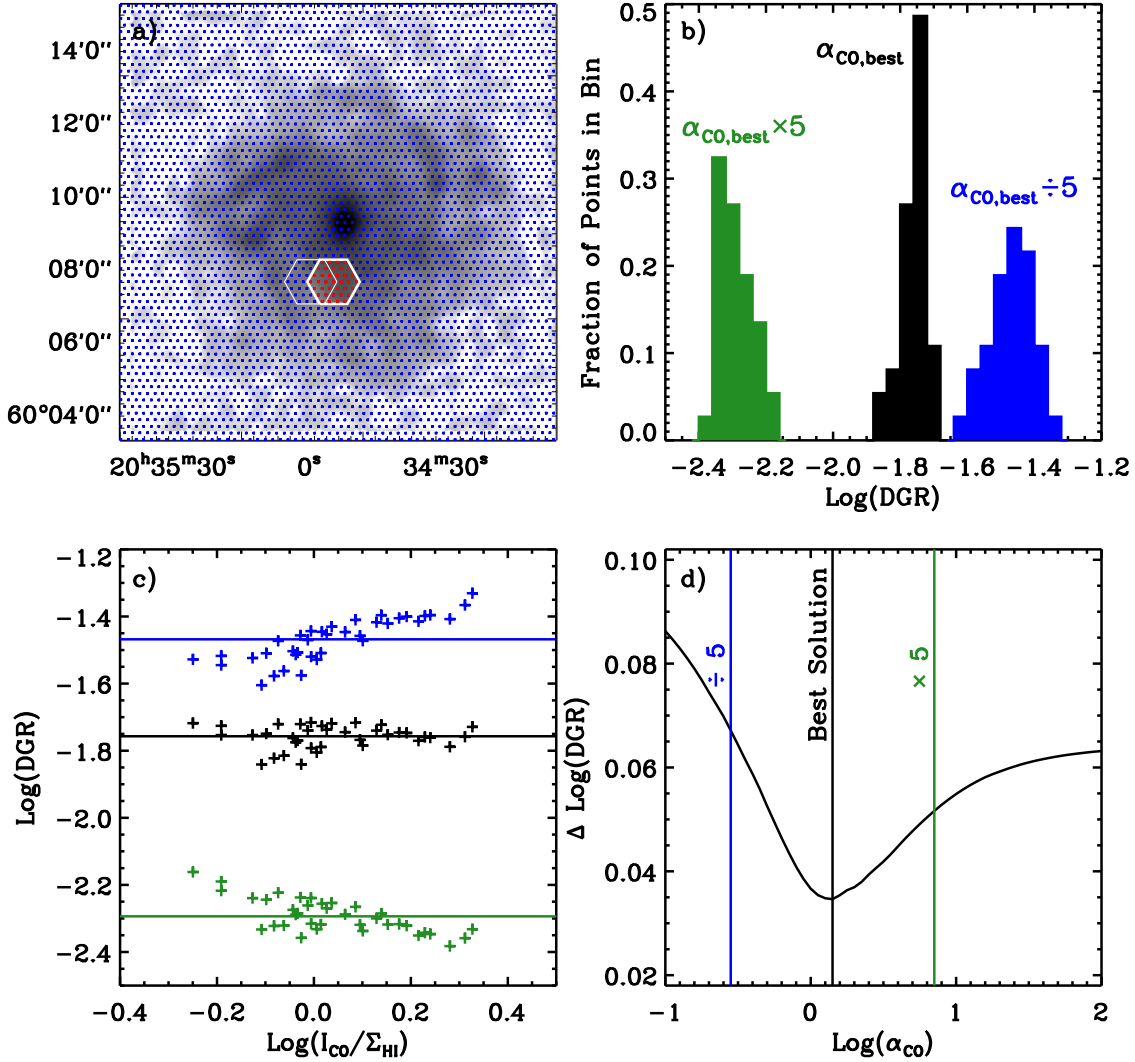
Figure 1 for an example). The 37-point solution pixels are a compromise between small region sizes and having a sufficient number of independent measurements to minimize statistical noise. The solution pixels tile the galaxy with center-to-center spacing of 37.5". Thus, neighboring solution pixels are not independent and share  $\sim 40\%$  of their sampling points. The overlap between solution pixels is illustrated in Figure 1. Such a tiling is optimal because it fully samples the data and ensures that the final results are not dependent on the placement of the solution pixels. The solution pixels correspond to physical scales ranging from  $\sim 0.6$  kpc to 3.9 kpc.

### 3.2. Minimizing the DGR Scatter

For each sampling point  $i$  in the solution pixel, the measurements of  $\Sigma_{\text{D},i}$ ,  $\Sigma_{\text{HI},i}$  and  $\text{I}_{\text{CO},i}$  along with an assumed  $\alpha_{\text{CO}}$  determine  $\text{DGR}_i$ . We step through a grid of  $\alpha_{\text{CO}}$  values to find the  $\alpha_{\text{CO}}$  that results in the most uniform DGR for all  $\text{DGR}_i$  in the solution pixel. In all solutions presented here, we use an  $\alpha_{\text{CO}}$  grid with 0.05 dex spacing, spanning the range  $\alpha_{\text{CO}} = 0.1 - 100 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ .

We determine the most “uniform” DGR in a solution pixel by minimizing the scatter in the  $\text{DGR}_i$  values as a function of  $\alpha_{\text{CO}}$ . The scatter is measured with a robust estimator of the standard deviation<sup>4</sup> of the logarithm of the  $\text{DGR}_i$  values—this technique appears to work best because outliers have little effect on the measured scatter because of both the logarithmic units and the outlier suppression. After measuring the scatter in the DGR at every  $\alpha_{\text{CO}}$  value, we find the  $\alpha_{\text{CO}}$  at which the scatter

<sup>4</sup> We use the IDL implementation of Tukey’s biweight mean (Press et al. 2002) `biweight_mean.pro`.



**Figure 1.** Illustration of the technique to determine DGR and  $\alpha_{\text{CO}}$  for a single solution pixel in NGC 6946. Panel a) shows the CO map from HERACLES overlaid with the half-beam spaced sampling grid. The solution pixel in question is shown with a white hexagon and the 37 individual sampling points included in the solution are shown in red. A neighboring solution pixel is also highlighted with a thin white line to show how the pixels are arranged and that neighboring solution pixels share  $\sim 40\%$  of their sampling points. Panel b) illustrates that the scatter in the DGR changes as a function of  $\alpha_{\text{CO}}$ . Here we have plotted histograms of the measured  $\text{DGR}_i$  values in this solution pixel at three different values of  $\alpha_{\text{CO}}$  (the optimal value in black and a factor of 5 above and below this value in green and blue, respectively). Panel c) illustrates that this scatter originates in variation of DGR as a function of CO/HI when  $\alpha_{\text{CO}}$  is not at the optimal value. We show this by plotting the 37  $\text{DGR}_i$  values as a function of CO/HI ratio for the same three  $\alpha_{\text{CO}}$  values shown in panel b). The horizontal lines indicate the mean DGR for each set of points. The slope in DGR vs CO/HI space is minimized at the optimal  $\alpha_{\text{CO}}$ . Finally, in panel d) we show the scatter in the DGR at each value of the full  $\alpha_{\text{CO}}$  grid in black. The three highlighted  $\alpha_{\text{CO}}$  values are marked with vertical lines. Panel d) highlights the fact that the DGR scatter is minimized at the best fit  $\text{Log}(\alpha_{\text{CO}}) = 0.15 \pm 0.22$  in this region. The minimization of the scatter in  $\text{Log}(\text{DGR})$ , as shown in panel d), is the technique we have determined to be the most effective for determining  $\alpha_{\text{CO}}$  and DGR, using tests that are described in detail in the Appendix.

( $\Delta \log(\text{DGR})$ ) is minimized. This is taken to be our best fit  $\alpha_{\text{CO}}$  value for the region. We consider a solution to be found when a minimum has been located in the DGR scatter within the range of our  $\alpha_{\text{CO}}$  grid. This does not happen in every solution pixel—some do not have sufficient CO/HI contrast, others have too low S/N and for some the minimum is at the edge of the allowable range and the solution is not well-constrained. The failed solutions are not included in our further analysis.

An illustration of the technique is shown in Figure 1 for a region in NGC 6946. In panel a) we show the HERACLES CO J=(2–1) map of the galaxy with our

half-beam sampling grid, the hexagonal region shows the “solution pixel” in question, which includes 37 individual samples from the maps. Panels b) and c) show how varying  $\alpha_{\text{CO}}$  affects the mean DGR and scatter for the points in the region, illustrating how the scatter increases away from the best  $\alpha_{\text{CO}}$  value. Panel d) shows the scatter as a function of  $\alpha_{\text{CO}}$  for the whole  $\alpha_{\text{CO}}$  grid. A clear minimum exists for this solution pixel at  $\alpha_{\text{CO}} \sim 1.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ .

### 3.3. Statistical Uncertainties on $\alpha_{\text{CO}}$ and DGR

We judge the uncertainties on the “best fit”  $\alpha_{\text{CO}}$  and DGR in several ways. First, to take into account statistical errors, we perform a Monte Carlo test on the solutions by adding random noise to our measured  $\Sigma_{\text{D}}$ ,  $\Sigma_{\text{HI}}$  and  $\text{I}_{\text{CO}}$  values according to each point’s measurement errors. We repeat the solution with the randomly perturbed data values 100 times and find the standard deviation of the results. We also perform a “bootstrapping” trial, which tests the sensitivity of each solution to individual measurements. In each bootstrap iteration for a given solution pixel, we randomly select 37 sampling points, with replacement, and derive the solution. The bootstrap procedure is repeated 100 times for each solution pixel and we measure the resulting standard deviation of the  $\alpha_{\text{CO}}$  values. The standard deviations from the Monte Carlo and bootstrapping iterations are added in quadrature to produce the final quoted error for the  $\alpha_{\text{CO}}$  values we determine. In addition, to check these uncertainties we also estimate scatter and bias in  $\alpha_{\text{CO}}$  for the given technique from our simulated data trials described in the Appendix, based on the median CO S/N in the solution pixel and the measured minimum of  $\Delta\log(\text{DGR})$ . The uncertainties from Monte Carlo plus bootstrapping are comparable to what we expect given the simulated data trials.

### 3.4. Systematic Uncertainties on $\alpha_{\text{CO}}$

#### 3.4.1. Uncertainties on $\alpha_{\text{CO}}$ from $R_{21}$ Variations

In the following, we report  $\alpha_{\text{CO}}$  appropriate for the  $(1-0)$  line, since it is the canonical CO-to- $\text{H}_2$  conversion factor that most observational and theoretical studies utilize. To do so we have converted between  $(2-1)$  (which we have directly measured) and  $(1-0)$  using a fixed line ratio  $R_{21} = 0.7$ . This value of  $R_{21}$  is the average found for the entire HERACLES sample (E. Rosolowsky, private communication). Deviations from the  $R_{21}$  value we have assumed will result in systematic offsets in the  $(1-0)$  conversion factor, while the  $(2-1)$  conversion factor will be unaffected since it is what we have directly measured. To quantify the potential  $(1-0)$   $\alpha_{\text{CO}}$  offsets, we have investigated the variability of  $R_{21}$  in those galaxies with publicly available CO  $\text{J}=(1-0)$  maps from the Nobeyama survey of nearby spiral galaxies (Kuno et al. 2007). Galaxies that have Nobeyama maps are marked with an asterisk in Table 1. The details of this comparison can be found in the Appendix. We find that deviations from  $R_{21} = 0.7$  can cause small systematic shifts in  $\alpha_{\text{CO}}$  appropriate for the  $(1-0)$  line, but the magnitude of the shifts are generally within the uncertainties on the  $\alpha_{\text{CO}}$  solutions (i.e. typically less than 0.2 dex). We note that variations of  $R_{21}$  within a pixel would introduce additional systematic uncertainties on  $\alpha_{\text{CO}}$ .

#### 3.4.2. Variations of $\Sigma_{\text{D}}$ Linearity Within Solution Pixels

An assumption we make in using this technique is that the dust tracer we employ (here  $\Sigma_{\text{D}}$ ) linearly tracks the true dust mass surface density. For the purposes of characterizing systematic uncertainties on  $\alpha_{\text{CO}}$ , all that matters is that within a given solution pixel  $\Sigma_{\text{D}}$  is a linear tracer. This is because we calibrate DGR based on the  $\Sigma_{\text{D}}$  values themselves, so any multiplicative constant term cancels out in Equation 3. In theory, we could use a different linear dust mass surface density tracer in each

pixel and still derive  $\alpha_{\text{CO}}$  without issues. Systematic uncertainties in the absolute calibration of  $\Sigma_{\text{D}}$  show up in the DGR and we discuss those in Section 3.5.

Non-linearity may be introduced in  $\Sigma_{\text{D}}$  within a solution pixel if dust emissivity or DGR vary with ISM phase. A variety of observations have suggested that dust emissivity increases in molecular gas relative to atomic gas (note, however, that most of the studies use CO to trace molecular gas and may interpret variations in  $\alpha_{\text{CO}}$  as changes in emissivity). Recent work has suggested that the dust emissivity increases by a factor of  $\sim 2$  between the atomic and molecular ISM (Planck Collaboration et al. 2011b; Martin et al. 2012). If the dust in molecular regions has a higher emissivity,  $\Sigma_{\text{D}}$  will overestimate the amount of dust there, causing us to overestimate the amount of gas. In that case, we would recover a higher  $\alpha_{\text{CO}}$  than actually exists. As a first approximation, our measured  $\alpha_{\text{CO}}$  would be too high by the change in emissivity between atomic and molecular phases, a factor of  $\sim 2$  based on the previously mentioned results. An increase in the DGR between atomic and molecular phases would also behave in this way, but we expect such changes to be less than a factor of two (see Section 4.5 of Leroy et al. 2011, for more detailed arguments).

Another potential source of non-linearity in  $\Sigma_{\text{D}}$  is ISM-phase dependent systematic biases in measuring  $\Sigma_{\text{D}}$  from SED modeling. Because warm dust will radiate more strongly per unit mass than cold dust at all wavelengths, the SED will not clearly reflect the presence of cold dust unless it dominates the mass. This means that the SED fitting technique is not sensitive to cold dust contained in GMC interiors ( $A_V \gtrsim 1$ ) at our spatial resolution. The fraction of the dust mass in these interiors, assuming a spherical cloud with uniform density and total  $A_V \approx 8$  mag, is  $\sim 40\%$  (this estimate agrees well with recent extinction mapping measurements of Milky Way GMCs: Kainulainen et al. 2011; Lombardi et al. 2011). If we underestimate the mass of dust by missing cold dust in GMC interiors, we would underestimate the amount of molecular gas and adjust  $\alpha_{\text{CO}}$  downwards. The magnitude of this effect is at the factor of  $\sim 2$  level and opposite in direction to what we expect for dust emissivity or DGR increases in molecular clouds.

#### 3.4.3. Opaque $\text{H I}$

The HI maps we use have not been corrected for any optical depth effects (Walter et al. 2008). HI observations of M 31 at high spatial and spectral resolution have found that the total gas mass taking into account opacity effects was  $\sim 30\%$  higher (Braun et al. 2009). If optical depth effects are important, the optically-thin estimate for the atomic gas mass would be too low, resulting in our procedure determining a DGR that is too high (excess dust compared to the amount of gas). In the molecular regions, then, we will expect too much gas based on that same DGR, and consequently increase  $\alpha_{\text{CO}}$ . Therefore, the effect of HI opacity is to overestimate  $\alpha_{\text{CO}}$ . We expect the magnitude of such an effect to be a factor of  $\sim 1.3$  or less, which is well within the statistical uncertainties we achieve on the  $\alpha_{\text{CO}}$  measurements.

### 3.5. Systematic Uncertainties on DGR

#### 3.5.1. Absolute Calibration of $\Sigma_{\text{D}}$

As we have discussed above, as long as  $\Sigma_{\text{D}}$  is a linear tracer of true dust mass surface density within a given solution pixel, its absolute calibration has no effect on the  $\alpha_{\text{CO}}$  value we measure. The same is not true for the DGR value. Any uncertainties on the calibration of  $\Sigma_{\text{D}}$  will be directly reflected in the DGR measurement. The  $\Sigma_{\text{D}}$  values we used are from fits of the Draine & Li (2007) models to the IR SED using the Milky Way  $R_V = 3.1$  grain model. The extent to which the appropriate dust emissivity  $\kappa_\nu$  deviates from the value used by this model represents a systematic uncertainty on the DGR values we derive. Our knowledge of  $\kappa_\nu$  in different environments is limited, but there are constraints from observations of dust extinction curves and depletions in the Large and Small Magellanic Clouds (c.f. Weingartner & Draine 2001). Draine et al. (2007) demonstrated that the  $\Sigma_{\text{D}}$  values decreased by a factor of  $\sim 1.2$  when the LMC or SMC dust model was used instead of the MW model. Given that our sample is largely dominated by spiral galaxies and hence does not probe environments with metallicity comparable to the SMC (due to the faintness of CO in such regions and our S/N limitations), we expect that the systematic uncertainties on our DGR when comparing with other results from Draine & Li (2007) model fits is small. However, other dust models may have different prescriptions for  $\kappa_\nu$ , so comparison of our DGR values to results from studies not using the Draine & Li (2007) models will have systematic offsets.

#### 4. RESULTS

##### 4.1. NGC 0628 Results Example

We divided each of the 26 galaxies in our sample into solution pixels and performed the simultaneous solution for DGR and  $\alpha_{\text{CO}}$  in each pixel. As an example, we present the results for NGC 0628 in the following section. The results for all solution pixels in all galaxies can be seen in the Appendix.

Figure 2 shows, from left to right, the HI, CO and  $\Sigma_{\text{D}}$  maps used in our analysis. The circles overlaid on the map represent the centers of the solution pixels we have defined. Figure 3 shows the same circles representing the solution pixel centers, now filled in with a color representing the best  $\alpha_{\text{CO}}$  solution for that pixel on the left, a gray scale showing the uncertainty on that  $\alpha_{\text{CO}}$  solution in the middle, and the DGR on the right. Finally, in Figure 4 we show these measured  $\alpha_{\text{CO}}$  values as a function of galactocentric radius ( $r_{25}$ ). For comparison, Figure 4 also shows the local Milky Way  $\alpha_{\text{CO}} = 4.4 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  with a solid horizontal line (dotted lines show a factor of 2 above and below, see Section 5.1 for details on how the Milky Way value has been measured). We note that the Milky Way may show a gradient of  $\alpha_{\text{CO}}$  with radius (also discussed in Section 5.1), but for purposes of comparison with the most widely-used conversion factor we use a constant  $\alpha_{\text{CO}}$  on all plots.

In general, NGC 0628 shows  $\alpha_{\text{CO}}$  consistent with the Milky Way value within a factor of 2 at all galactocentric radii. Outside a radius of  $r_{25} \sim 0.6$  we find few good solutions. There is a weak trend for lower  $\alpha_{\text{CO}}$  at smaller radii, with the central solution pixel having a conversion factor  $\alpha_{\text{CO}} = 2.2 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ . Recent work by Blanc et al. (submitted) found consistent results for  $\alpha_{\text{CO}}$  by inverting the star-formation rate surface density

map using a fixed molecular gas depletion time.

##### 4.2. Completeness of Solutions

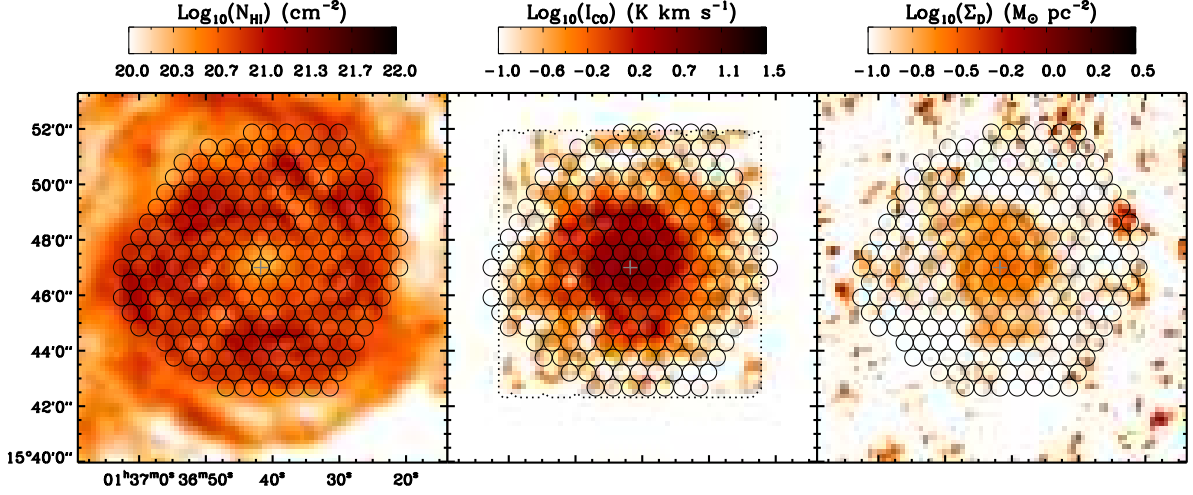
The technique we have used to solve for DGR and  $\alpha_{\text{CO}}$  simultaneously only works if there is sufficient S/N in the CO map and a range of CO/HI ratios in each solution pixel. These two constraints impose limits on where in the galaxies we can achieve solutions. In order to perform statistical tests on our sample of  $\alpha_{\text{CO}}$  and DGR values, we need to understand what biases these limits introduce into our results. For example, the failure of the technique in regions with low CO S/N generally limits our good solutions to the inner parts of galaxies, where metallicity tends to be higher. In order to judge the existence of trends in  $\alpha_{\text{CO}}$  versus metallicity, we therefore need to understand where we have achieved good solutions.

To investigate these effects, we have examined the fraction of solution pixels that have solutions and the uncertainty on the derived  $\alpha_{\text{CO}}$  as a function of the range of CO/HI ratios and mean  $\text{I}_{\text{CO}}$  in a pixel. In general, the HI in our target galaxies has a quite flat radial profile, while the CO drops off approximately exponentially (Schruba et al. 2011). Because of these trends, wherever there is sufficient signal in CO to achieve a good solution, the CO/HI range is adequate as well. Thus, we find that the mean  $\text{I}_{\text{CO}}$  of a solution pixel is the best predictor for the existence and quality of a solution. Figure 5 shows the fraction of pixels with solutions and the average uncertainty on the solutions as a function of the mean  $\text{I}_{\text{CO}}$ . We identify a cut-off at  $\text{I}_{\text{CO}} > 1 \text{ K km s}^{-1}$  above which we obtain solutions  $> 90\%$  of the time and those solutions have an average uncertainty of  $< 0.5$  dex. For any statistical analysis that follows we use only pixels above this cut-off.

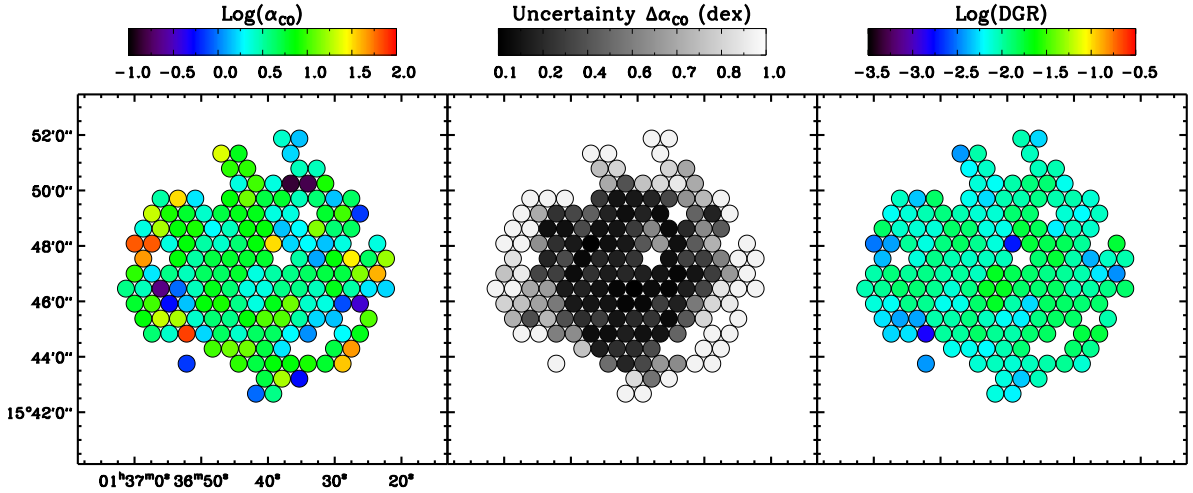
##### 4.3. Properties of Full-Sample $\alpha_{\text{CO}}$ Solutions

In Tables 4 and 5 we list the average  $\alpha_{\text{CO}}$  derived galaxy by galaxy and for the full sample. These averages only include solution pixels where  $\text{I}_{\text{CO}} > 1 \text{ K km s}^{-1}$ . The first two columns of Table 5 list the mean and standard deviation of the individual solution pixel measurements. This approach treats each solution pixel equally, regardless of how strongly it contributes to the total molecular gas mass. The third column instead lists the mean  $\alpha_{\text{CO}}$  derived from the total  $\Sigma_{\text{H}_2}$  and the total  $\text{I}_{\text{CO}}$  for the galaxy (above  $\text{I}_{\text{CO}} = 1 \text{ K km s}^{-1}$ ), which is equivalent to a mean where the pixels are weighted by their  $\text{I}_{\text{CO}}$ . If a single  $\alpha_{\text{CO}}$  value were to be applied to the data, this would be the optimal value to use. For most galaxies, the CO weighted mean is higher than the straight mean of the solution pixels. This is due to the fact that the molecular gas is not evenly distributed across the galaxy and the area-weighted average is different than the molecular gas weighted average.

Figure 6 shows several histograms illustrating the distribution of our measured  $\alpha_{\text{CO}}$  values. The mean, derived with several different weighting schemes, is listed in Table 5. The top panels of Figure 6 show histograms of all solution pixels while the bottom panels show histograms of the galaxy averages from Table 4. On these histograms we highlight galaxies with high inclinations in green ( $i > 65^\circ$ ). It is clear that the high inclination galaxies tend to have higher  $\alpha_{\text{CO}}$  on average than the



**Figure 2.** The HI, CO and  $\Sigma_D$  maps for NGC 0628, from left to right. The centers of the pixels in which we perform the simultaneous  $\alpha_{CO}$  and DGR solutions are shown as circles overlaid on the images. The gray cross shows the central solution pixel for the galaxy. On the middle panel, the coverage of the HERACLES CO map is shown with a dotted line. Similar plots for all galaxies in the sample can be found in the Appendix.



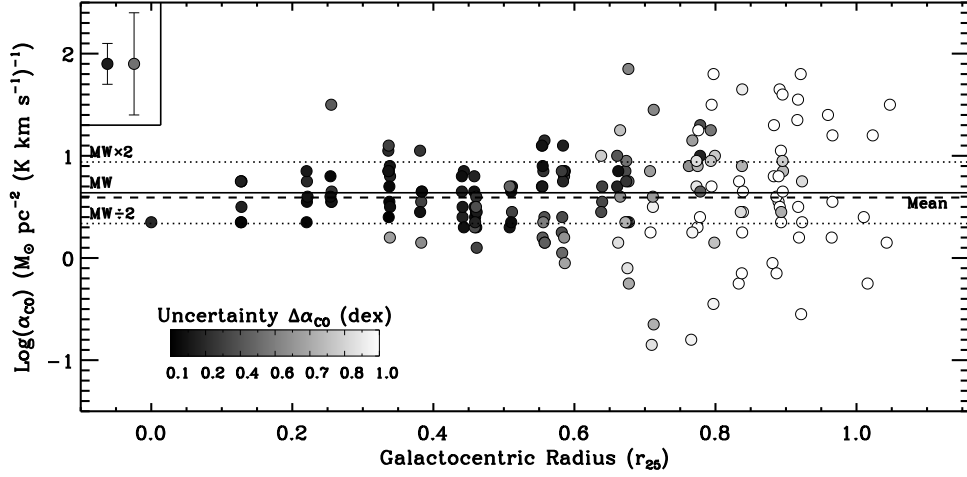
**Figure 3.** Results of the simultaneous  $\alpha_{CO}$  and DGR solutions for NGC 0628. The centers of the solution pixels are represented with circles as shown on Figure 2. The left panel shows the resulting  $\alpha_{CO}$ , the middle shows the uncertainty on that value and the right shows the DGR. Solution pixels where the technique failed do not appear. For NGC 0628 it is clear that where there are good solutions (as judged by the uncertainty on  $\alpha_{CO}$  in the middle panel) most of the values are close to the MW  $\text{Log}(\alpha_{CO}) = 0.64$ . In pixels with good solutions, the DGR varies smoothly across the galaxy, which shows that our assumption of a single DGR in each solution pixel is self-consistent.

more face-on galaxies. In the highest inclination galaxies the pixel will include contributions from gas at larger radii which tends to have lower DGR and less molecular gas. This is equivalent to the challenge faced by Leroy et al. (2011) in the SMC, where some of the HI along the line of sight originates in an essentially dust-free envelope, and in M 31, where regions on the minor axis of the galaxy have contributions from gas and dust at a variety of radii. In addition, optical depth effects for HI may be accentuated for highly inclined galaxies. All galaxies with  $i > 65^\circ$  show average  $\alpha_{CO}$  above the mean (except for NGC 0925, which has a somewhat uncertain inclination; de Blok et al. 2008). We thus eliminate all galaxies with  $i > 65^\circ$ , leaving 782 total  $\alpha_{CO}$  measurements.

In Table 5 we list the average values of  $\alpha_{CO}$  for the full

galaxy sample. Excluding the high inclination galaxies, we find an average  $\alpha_{CO} = 2.6 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  for the individual solution pixel results. Weighted by  $I_{CO}$ , the average value is slightly higher,  $\alpha_{CO} = 2.9 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ . To avoid highly resolved galaxies like NGC 5457 and 6946 contributing more points to the average, we also calculate averages where each galaxy contributes uniformly. These are listed in the last two columns of Table 5. The average value for our sample,  $\alpha_{CO} = 3.1 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ , is only slightly lower than what is found in the Milky Way disk.

The standard deviation in  $\alpha_{CO}$  is 0.38 dex, treating all lines of sight equally (with our  $I_{CO}$  and inclination cut-offs). A key question we would like to answer is to what degree this scatter represents 1) true scatter within each galaxy, 2) galaxy-to-galaxy offsets or 3) variation



**Figure 4.**  $\alpha_{\text{CO}}$  solutions for NGC 0628 as a function of galactocentric radius (in units of  $r_{25}$ ). The solid horizontal line shows the MW  $\alpha_{\text{CO}} = 4.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  (note that the MW could potentially have a gradient in  $\alpha_{\text{CO}}$  with radius that we do not show here). The dotted lines show a factor of 2 above and below the MW value. The dashed horizontal line shows the average value for NGC 0628. The gray scale color of the points represents the uncertainty on  $\alpha_{\text{CO}}$  as shown in Figure 3—darker points have lower uncertainties. For comparison with the gray color table, two representative error bars for the  $\alpha_{\text{CO}}$  solutions are shown in the top left corner of the plot. For NGC 0628, almost all of the high confidence  $\alpha_{\text{CO}}$  solutions are within a factor of 2 of the MW value.

**Table 4**  
Galaxy Average  $\alpha_{\text{CO}}$

Galaxy	Mean $\alpha_{\text{CO}}$	Std. Dev. (dex)	CO Weighted Mean $\alpha_{\text{CO}}$	# Meas.
NGC 0337	22.4	16.2–31.0 (0.14)	21.8	2
NGC 0628	3.9	2.1–7.4 (0.28)	5.1	67
NGC 0925	10.0	6.8–14.7 (0.17)	10.0	1
NGC 2841	5.0	2.5–10.3 (0.31)	5.7	19
NGC 2976	3.3	0.9–12.5 (0.58)	4.7	18
NGC 3077	4.6	2.3–9.4 (0.31)	5.4	7
NGC 3184	5.3	2.9–9.5 (0.26)	6.3	43
NGC 3198	11.0	6.4–18.9 (0.24)	11.9	11
NGC 3351	2.7	1.0–6.9 (0.41)	2.9	28
NGC 3521	7.6	4.9–11.8 (0.19)	7.3	42
NGC 3627	1.2	0.4–3.3 (0.44)	1.8	43
NGC 3938	5.5	4.1–7.5 (0.13)	5.8	19
NGC 4236	...	...	...	0
NGC 4254	3.4	2.1–5.7 (0.22)	4.7	46
NGC 4321	2.2	1.1–4.6 (0.32)	2.2	57
NGC 4536	2.6	1.0–6.7 (0.41)	2.6	13
NGC 4569	1.1	0.3–4.1 (0.57)	1.2	14
NGC 4625	...	...	...	0
NGC 4631	10.8	5.6–19.5 (0.26)	9.8	40
NGC 4725	1.2	0.4–3.2 (0.44)	1.8	7
NGC 4736	1.0	0.5–2.0 (0.29)	1.1	33
NGC 5055	3.7	1.9–7.4 (0.30)	4.0	86
NGC 5457	2.3	1.1–4.8 (0.32)	2.9	142
NGC 5713	4.6	1.7–12.6 (0.44)	5.4	13
NGC 6946	2.0	0.9–4.4 (0.35)	1.8	158
NGC 7331	9.8	6.2–15.3 (0.20)	10.7	32

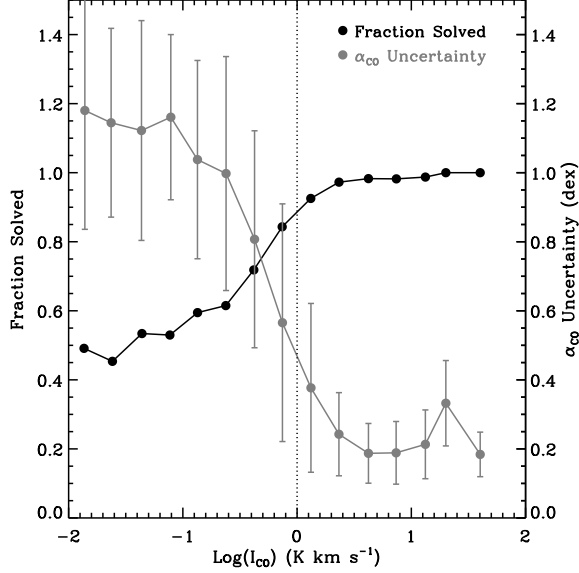
**Note.** — Averages include only solution pixels with  $\text{I}_{\text{CO}} > 1 \text{ K km s}^{-1}$ . The number of measurements meeting this criterion are shown in the last column of the table.

**Table 5**  
Sample Average  $\alpha_{\text{CO}}$

Sample	Mean $\alpha_{\text{CO}}$ all L.O.S.	Std. Dev. (dex)	CO Weighted Mean $\alpha_{\text{CO}}$	Gal. Weighted Mean $\alpha_{\text{CO}}$	Gal & CO Weighted Mean $\alpha_{\text{CO}}$
Incl $< 65^\circ$	2.6	1.0–6.6 (0.41)	2.9	3.1	3.5
Incl $> 65^\circ$	7.2	3.0–17.6 (0.39)	8.2	6.5	6.7

**Note.** — Averages include only solution pixels with  $I_{\text{CO}} > 1 \text{ K km s}^{-1}$ .





**Figure 5.** The completeness and quality of our  $\alpha_{\text{CO}}$  solutions as a function of the mean  $I_{\text{CO}}$  in a solution pixel. The black points show the fraction of solution pixels where a solution was found. The gray points show the mean uncertainty on  $\alpha_{\text{CO}}$  with error bars showing the standard deviation. For  $I_{\text{CO}} > 1 \text{ K km s}^{-1}$ ,  $> 90\%$  of solution pixels have solutions and their typical uncertainty is  $< 0.5$  dex. We use this 90% completeness cut to select a well-defined sample of  $\alpha_{\text{CO}}$  measurements for statistical analysis in the following work.

of  $\alpha_{\text{CO}}$  as a function of local parameters. If the scatter comes from variations with local environmental parameters, we may be able to generate a prescription for  $\alpha_{\text{CO}}$  as a function of other observables. In the following sections we explore the variations of  $\alpha_{\text{CO}}$  within and among our galaxies to understand if and why it varies.

#### 4.4. Radial Variations in $\alpha_{\text{CO}}$

In Figure 7 we present a summary of the  $\alpha_{\text{CO}}$  values we find as a function of galactocentric radius. Plots of  $\alpha_{\text{CO}}$  from each individual galaxy as a function of  $r_{25}$  are presented in the Appendix. Each individual solution that makes our  $I_{\text{CO}}$  and inclination cut is shown in Figure 7 with gray circles. We also display the mean and standard deviation of the  $\alpha_{\text{CO}}$  values in  $0.1 r_{25}$  bins for each galaxy (this mean treats all solution pixels equally). The top panel of Figure 7 shows the measured  $\alpha_{\text{CO}}$  and the bottom panel shows those same values normalized by each galaxy’s average  $\alpha_{\text{CO}}$  from Table 4.

The average radial profile of our galaxies is mostly flat as a function of  $r_{25}$ , but almost all galaxies show a decrease in  $\alpha_{\text{CO}}$  in the inner  $\sim 0.2 r_{25}$  compared to their average value. The mean central decrease is  $\sim 0.3 - 0.4$  dex, but it can be as much as 0.8 dex. For several galaxies this decrease leads to a central  $\alpha_{\text{CO}}$  value that is an order-of-magnitude lower than the MW  $\alpha_{\text{CO}}$  (e.g. NGC 4736, 5457 and 6946). The central depression persists even after correcting for differences in  $R_{21}$  (see the following Section for further discussion).

Normalizing each galaxy by its average  $\alpha_{\text{CO}}$  and making each galaxy contribute equally to the average leads to much smaller scatter at  $r_{25} > 0.3$  (this can be seen in the bottom panel of Figure 7 where the radial profiles show much less scatter than the individual measurements, which is not the case in the top, unnormalized

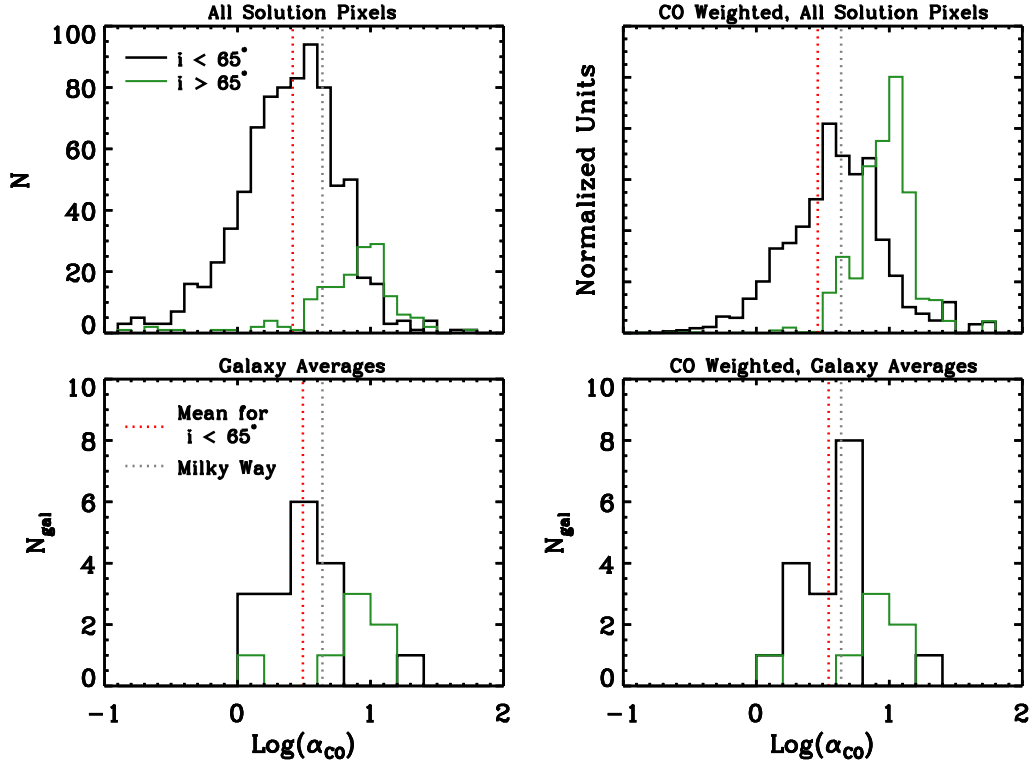
panel). Inside that radius, scatter in the normalized  $\alpha_{\text{CO}}$  profiles is reduced, but not by as much outside that radius, indicating that individual galaxies show different central profiles of  $\alpha_{\text{CO}}$ . The overall conclusions from examination of Figure 7 are: 1) outside  $r_{25} \sim 0.3$  most of the scatter in our  $\alpha_{\text{CO}}$  measurements can be explained by galaxy to galaxy differences, 2) inside that galactocentric radius, galaxy-specific trends in  $\alpha_{\text{CO}}$  dominate the scatter and 3) in general the inner region of galaxies shows  $\alpha_{\text{CO}}$  lower than the rest of the disk.

#### 4.5. $\alpha_{\text{CO}}$ in Galaxy Centers

In Table 6 we list the central  $\alpha_{\text{CO}}$  values and compare them to the MW value and the mean for the galaxy. Almost all of the central solution pixels have  $\alpha_{\text{CO}}$  lower than the galaxy mean. The galaxies NGC 3351, 3627, 4321, 4736, 5457 and 6946 show  $\alpha_{\text{CO}}$  values a factor of 5 or more lower than the MW value with  $3\sigma$  confidence. For 4736, 5457 and 6946, in particular, the central solution pixel has  $\alpha_{\text{CO}}$  an order-of-magnitude below the MW value. Only one galaxy, NGC 0337, shows a central  $\alpha_{\text{CO}}$  higher than the MW value at  $3\sigma$ . In Table 6, we also list the CO  $(2-1)/(1-0)$  ratio measured as described in Section 3.4.1. While the central solution pixels do tend to have higher  $R_{21}$  than the value we have adopted, the difference is less than a factor of 2 in all cases, and does not alter our main conclusions about the low  $(1-0)$  conversion factor in these regions. In particular, for the 10 galaxies with measured  $R_{21}$  and  $i < 65^\circ$ , the central  $\alpha_{\text{CO}}$  corrected for  $R_{21}$  is still on average 0.3 dex lower (i.e. a factor of 2) than the galaxy average.

The central solution pixels can be outliers from the rest of the pixels in our sample in the sense of having high CO/HI ratios. Since there are relatively few solution pixels with these conditions, they may not have been well represented in the simulated data we used to test the accuracy of the solution technique. High CO/HI ratios could potentially bias the results: if the S/N of the HI maps is almost always higher than the S/N of CO, the DGR scatter could be reduced in these conditions purely by decreasing the importance of CO in assessing the gas mass surface density. Since this bias would move the  $\alpha_{\text{CO}}$  results towards lower values in the centers, we performed a test to judge whether our low central  $\alpha_{\text{CO}}$  measurements could be due to this effect. The details of the test are described in the Appendix. In brief, we generated simulated datasets with known  $\alpha_{\text{CO}}$  values where the  $N_{\text{HI}}$ ,  $I_{\text{CO}}$  and  $\Sigma_{\text{D}}$  S/N is matched to the observations in each central solution pixel and performed Monte Carlo trials to see how well the known input  $\alpha_{\text{CO}}$  was recovered. In all cases, we found no evidence for a bias in the central solution pixel.

Taking into account the offset from  $R_{21}$  variations, our results show that the central  $\alpha_{\text{CO}}$  in NGC 3351, 3627, 4321, 4736, 5457 and 6946 is lower than the MW value by a factor of 4 – 10. Many of these galaxies show  $\alpha_{\text{CO}}$  closer to the Milky Way value at larger radii, in line with the general trend seen in Figure 7. For NGC 3627, the mean  $\alpha_{\text{CO}}$  for the galaxy is low as well, suggesting that the central region is not distinct from the rest of the disk (this galaxy is an interacting member of the Leo Triplet, so it is unique in our sample). Conversely, examination of the individual galaxy  $\alpha_{\text{CO}}$  measurements as a function of radius (shown in the Appendix) for NGC 3351, 4321,

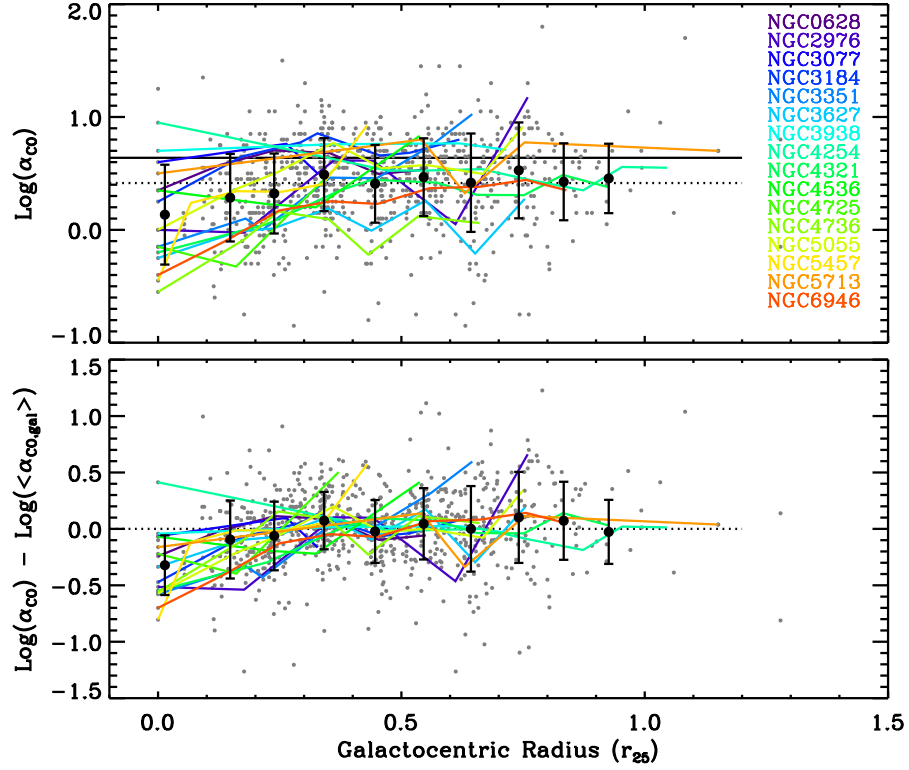


**Figure 6.** Histograms showing the distribution of  $\alpha_{\text{CO}}$  results with various weighting schemes. The averages are reported in Table 5. The panels show histograms of galaxies with  $i < 65^\circ$  in black and galaxies with  $i > 65^\circ$  in green. In each panel we highlight the mean value of  $\alpha_{\text{CO}}$  for galaxies with  $i < 65^\circ$  with a dotted vertical red line and the Milky Way  $\alpha_{\text{CO}}$  in gray. These histograms include solution pixels above the  $I_{\text{CO}} > 1 \text{ K km s}^{-1}$  cutoff. The top left panel shows the histogram of the solution pixels. The top right panel shows those same values weighted by their  $I_{\text{CO}}$ —this makes pixels contribute to this histogram in proportion to their molecular gas mass. The bottom panels show histograms of the average  $\alpha_{\text{CO}}$  from each galaxy as listed in Table 4. Galaxies with high inclinations tend to show a higher than average  $\alpha_{\text{CO}}$ , because the solution pixels include gas and dust at a range of radii. On average, we find  $\alpha_{\text{CO}}$  slightly lower than the MW value in our sample.

**Table 6**  
Central  $\alpha_{\text{CO}}$  Measurements

Galaxy	$\text{Log}_{10}(\alpha_{\text{CO,Cen}}) \pm \sigma$	$\Delta_{\text{MW}} = \text{Log}_{10}(\alpha_{\text{CO}}/\alpha_{\text{CO,MW}})$	$\Delta_{\text{MW}}/\sigma$	$\Delta_{\text{mean}} = \text{Log}_{10}(\alpha_{\text{CO}}/\langle\alpha_{\text{CO}}\rangle)$	$\Delta_{\text{mean}}/\sigma$	$r_{21}$	$\text{Log}_{10}(r_{21}/0.7)$
NGC 0337	$+1.25 \pm 0.17$	+0.61	3.6	-0.10	0.6	...	...
NGC 0628	$+0.35 \pm 0.24$	-0.29	1.2	-0.24	1.0	...	...
NGC 2976	$+0.00 \pm 0.49$	-0.64	1.3	-0.51	1.0	...	...
NGC 3077	$+0.60 \pm 0.17$	-0.04	0.2	-0.06	0.4	...	...
NGC 3184	$+0.25 \pm 0.16$	-0.39	2.5	-0.47	3.0	$0.77 \pm 0.05$	+0.04
NGC 3351	$-0.15 \pm 0.14$	-0.79	5.6	-0.58	4.1	$1.10 \pm 0.24$	+0.19
NGC 3627	$-0.25 \pm 0.14$	-0.89	6.3	-0.34	2.4	$0.54 \pm 0.05$	-0.12
NGC 3938	$+0.70 \pm 0.19$	+0.06	0.3	-0.04	0.2	...	...
NGC 4254	$+0.95 \pm 0.82$	+0.31	0.4	+0.41	0.5	$1.03 \pm 0.06$	+0.17
NGC 4321	$-0.20 \pm 0.17$	-0.84	4.8	-0.55	3.1	$1.25 \pm 0.16$	+0.25
NGC 4536	$+0.35 \pm 0.13$	-0.29	2.2	-0.07	0.5	$1.26 \pm 0.28$	+0.26
NGC 4625	$+1.05 \pm 0.41$	+0.41	1.0	...	...	...	...
NGC 4725	$-0.15 \pm 0.71$	-0.79	1.1	-0.22	0.3	...	...
NGC 4736	$-0.55 \pm 0.17$	-1.19	6.9	-0.56	3.2	$1.35 \pm 0.09$	+0.29
NGC 5055	$+0.00 \pm 0.25$	-0.64	2.6	-0.57	2.3	$1.10 \pm 0.08$	+0.20
NGC 5457	$-0.45 \pm 0.20$	-1.09	5.5	-0.80	4.1	$0.90 \pm 0.08$	+0.11
NGC 5713	$+0.50 \pm 0.25$	-0.14	0.6	-0.16	0.6	...	...
NGC 6946	$-0.40 \pm 0.31$	-1.04	3.4	-0.70	2.3	$1.07 \pm 0.14$	+0.19

**Note.** — Galaxies with  $i > 65^\circ$  have been omitted from the Table.



**Figure 7.** Solutions for  $\alpha_{\text{CO}}$  plotted versus their galactocentric radius ( $r_{25}$ ). The top panel shows the  $\alpha_{\text{CO}}$  solutions and the bottom panel shows the same values normalized by each galaxy's average  $\alpha_{\text{CO}}$  (listed in Table 4). All individual solutions are shown as gray points. The mean and standard deviation of all of the solutions in 0.1  $r_{25}$  bins are shown with black symbols (this mean treats all lines of sight equally). The solid black horizontal line in the top panel shows  $\alpha_{\text{CO}}$  for the Milky Way. The dotted black horizontal line shows the average, with no weighting, of all solution pixels:  $\alpha_{\text{CO}} = 2.6 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ . The radial profile for each galaxy is shown with a solid colored line. The average  $\alpha_{\text{CO}}$  radial profile of our galaxies is mostly flat as a function of  $r_{25}$  with a decrease in  $\alpha_{\text{CO}}$  towards the center of the galaxy. On average, the central  $\alpha_{\text{CO}}$  value is  $\sim 0.3$  dex lower than the rest of the galaxy.

4736, 5457 and 6946 demonstrates that these galaxies show an unresolved region of lower than average  $\alpha_{\text{CO}}$  in their centers (note that our solution pixel grid oversamples the data, so an unresolved central depression affects the  $r_{25} = 0$  point and the six adjacent solution pixels). The closest galaxy that shows a central depression is NGC 4736 at  $D=4.66$  Mpc. At this distance, our solution pixel covers a region of radius 0.8 kpc. Even for this nearby example, we do not resolve the central depression. We tested whether the depressions were resolved using a grid of independent solution pixels (i.e. not overlapping) and found that the depression only affected the central pixel, consistent with it being unresolved. We note that our ability to detect any central depression may be a function of the galaxy’s distance due to the increased size of the central solution pixel. Even at  $D=14.3$  Mpc, however, we detect a clear central depression in NGC 4321.

The type of nuclear activity in each galaxy is not a good predictor for whether or not it displays a central  $\alpha_{\text{CO}}$  depression. Of the galaxies that show the clearest central depression NGC 3351, 5457 and 6946 are classified as star-formation or HII region dominated, while NGC 4321 and 4736 have signatures of active galactic nucleus (AGN) or low-ionization nuclear emission-line region (LINER) activity (for details on the nuclear classifications, see Kennicutt et al. 2011). Several galaxies with flat radial  $\alpha_{\text{CO}}$  profiles do show evidence for AGN activity: NGC 3627, 4254, and 4725, for example. Enhanced AGN activity could potentially effect molecular gas properties in the nuclei (e.g. Krips et al. 2008), but the relatively weak AGN present in the KINGFISH galaxies may not dominate on the kiloparsec scales we study here.

To summarize, we find that several galaxies in our sample show central  $\alpha_{\text{CO}}$  values that are substantially lower than the Milky Way value and also well below the galaxy average. This appears to take the form of depression in the central region that is unresolved by our solution pixel grid. We discuss these central regions and the physical conditions that may lead to low  $\alpha_{\text{CO}}$  further in Section 6.3.

#### 4.6. Correlations of $\alpha_{\text{CO}}$ with Environmental Parameters

Variations in  $\alpha_{\text{CO}}$  could potentially be related to variations in the local environmental conditions including metallicity, ISM pressure, interstellar radiation field strength, gas temperature, dust properties or other variables. Correlations between  $\alpha_{\text{CO}}$  and quantities that trace these environmental conditions may allow us to identify the drivers of  $\alpha_{\text{CO}}$  variations. They may also provide tools to predict the appropriate  $\alpha_{\text{CO}}$  in a given environment. In the following, we examine the correlations of our measured  $\alpha_{\text{CO}}$  with several observables that trace ISM conditions. For each tracer, we use the average value in each solution pixel. The physical interpretation of these correlations or lack thereof is discussed in Section 6.1.

In Figure 8 we plot our measured  $\alpha_{\text{CO}}$  values as a function of the average radiation field intensity ( $\bar{U}$ ), the PAH fraction ( $q_{\text{PAH}}$ ), metallicity ( $12+\text{Log}(\text{O}/\text{H})$ ), stellar mass surface density ( $\Sigma_*$ ), star-formation rate surface density ( $\Sigma_{\text{SFR}}$ ) and the dust mass surface density ( $\Sigma_{\text{D}}$ ). Each panel shows the individual measurements with gray sym-

**Table 7**  
 $\alpha_{\text{CO}}$  Correlation Properties

Log( $\alpha_{\text{CO}}$ ) vs. Variable	Correlation <sup>a</sup> Coeff.	$\sigma$ from Null	Linear Fit <sup>b</sup>	
			Offset	Slope
$r_{25}$	+0.19	5.2	0.29	+0.29
$\text{Log}(\bar{U})$	-0.19	5.2	0.50	-0.33
$q_{\text{PAH}}$ (%)	+0.13	3.7	0.11	+0.08
$12+\text{Log}(\text{O}/\text{H})$	-0.05	1.4	2.39	-0.24
$\text{Log}(\Sigma_*)$	-0.25	7.1	1.05	-0.33
$\text{Log}(\Sigma_{\text{D}})$	-0.15	4.1	0.26	-0.22
$\text{Log}(\Sigma_{\text{SFR}})$	-0.11	3.2	0.06	-0.14

**Note.** — These correlations are shown in Figure 8.

<sup>a</sup> Spearman rank correlation coefficient.

<sup>b</sup> Correlation with metallicity using a homogeneous sample of metallicity measurements is discussed in Section 4.6.1.

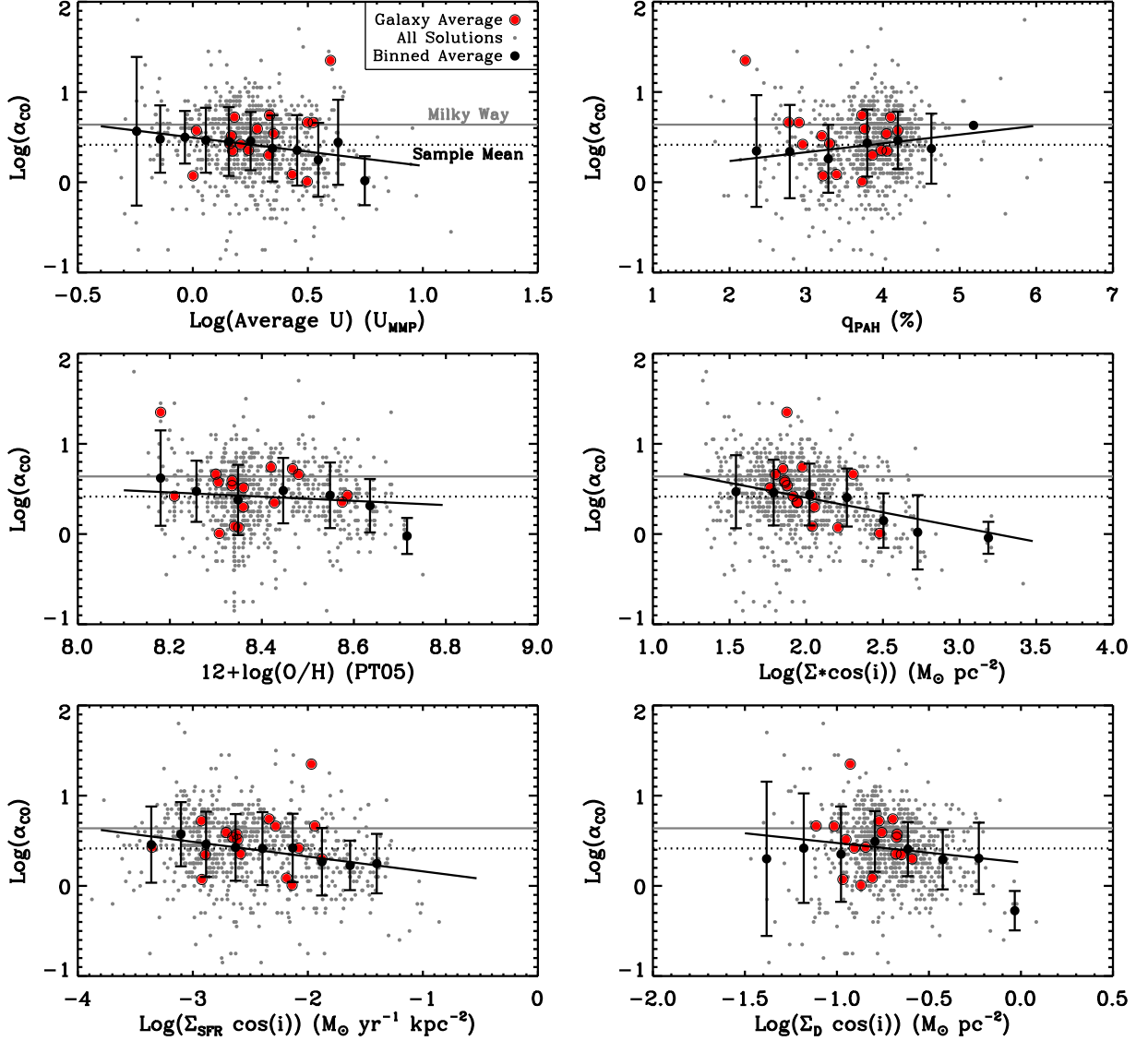
bols and the average for the galaxies with red symbols. The Milky Way  $\alpha_{\text{CO}}$  is highlighted with a horizontal gray line and the mean  $\alpha_{\text{CO}}$  treating all solution pixels equally ( $\alpha_{\text{CO}} = 2.6 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ ) is shown with a dashed horizontal line. Overlaid on each panel is the binned mean and standard deviation and a linear fit to the gray points. In Table 7 we list the linear fit results as well as the rank correlation coefficient for each panel and its significance (in standard deviations away from the null hypothesis). The rank correlation coefficients suggest there are significant correlations between  $\alpha_{\text{CO}}$  and all of the variables except metallicity. Due to potential inconsistencies between various metallicity measurements and incomplete knowledge of metallicity gradients in some galaxies, we examine the trends with metallicity separately in Section 4.6.1.

Several other radiation field properties are measured from the dust SED modeling. These include  $U_{\text{min}}$ , the minimum radiation field heating the dust, and  $f_{\text{PDR}}$  the fraction of the dust luminosity that arises in “PDR-like” regions where  $U > 100 U_{\text{MMP}}$ . We have investigated the dependence of  $\alpha_{\text{CO}}$  on these quantities and find weak trends with low significance.

The existence of a correlation between  $\alpha_{\text{CO}}$  and environmental parameters does not directly identify the cause of the variations in  $\alpha_{\text{CO}}$ , particularly since all of the parameters change radially to first order. In Figure 9 we illustrate the radial variations of the same variables by plotting them normalized by their average value as a function of  $r_{25}$ . All of the variables show significant correlations with radius. Table 8 lists the correlation coefficients and linear fits to the normalized radial profiles of the parameters. In all cases, the correlation of the variables with  $r_{25}$  is more significant than the correlation of  $\alpha_{\text{CO}}$  with those variables.

If all of the variations of these parameters were primarily related to radius, we would not expect to find stronger correlations between  $\alpha_{\text{CO}}$  and any parameter than between  $\alpha_{\text{CO}}$  and radius. Our results suggest, however, that the correlation between  $\alpha_{\text{CO}}$  and  $\Sigma_*$  is stronger ( $r_s = -0.25$ ) and more significant ( $7.1\sigma$ ) than the correlation with radius  $r_{25}$  ( $r_s = +0.19$ ,  $5.2\sigma$ ). One possible explanation is that our  $\Sigma_*$  measurement may trace the stellar profile better than  $r_{25}$  itself. Other potential explanations for the correlation of  $\alpha_{\text{CO}}$  with  $\Sigma_*$  will be discussed in Section 6.1.

Figure 7 illustrates that the normalized radial profile of

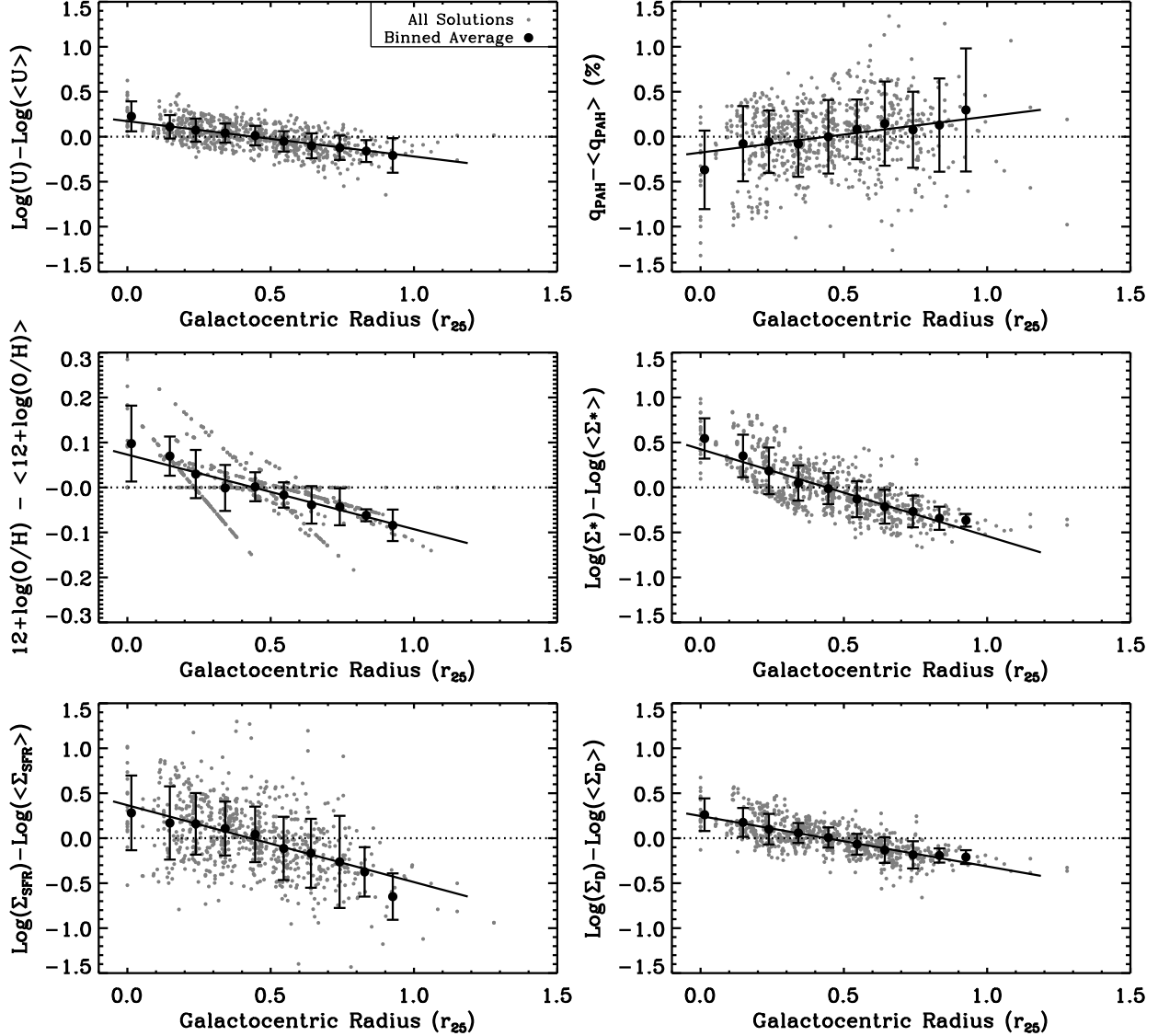


**Figure 8.**  $\alpha_{\text{CO}}$  as a function of environmental parameters. The panels show  $\alpha_{\text{CO}}$  plotted versus average radiation field intensity ( $\bar{U}$ ; top-left) and PAH fraction ( $q_{\text{PAH}}$ ; top-right) from the Aniano et al. (2012) fits, metallicity ( $12+\log(\text{O}/\text{H})$ ; middle-left), stellar mass surface density ( $\Sigma_*$ ; middle-right), star-formation rate surface density ( $\Sigma_{\text{SFR}}$ ; lower-left) and dust mass surface density ( $\Sigma_{\text{D}}$ ; lower-right). The solid gray line shows the Milky Way  $\alpha_{\text{CO}}$  and the dotted black line shows the sample average  $\alpha_{\text{CO}} = 2.6 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ , treating all solution pixels equally. Individual  $\alpha_{\text{CO}}$  solutions above our  $\text{I}_{\text{CO}}$  and inclination cuts are shown with gray symbols. The mean and standard deviation of those values in bins are shown with black circles and error bars. A linear fit to the measurements is shown with a black line. The mean values for all galaxies are shown with red circles. All variables except for metallicity show a statistically significant correlation with  $\alpha_{\text{CO}}$ . None of these correlations allow  $\alpha_{\text{CO}}$  to be predicted with significantly better precision than the scaling with  $r_{25}$ . However, the extreme values of  $\Sigma_{\text{SFR}}$  ( $> 0.5 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ) and  $\Sigma_*$  ( $> 1000 \text{ M}_{\odot} \text{ pc}^{-2}$ ) are always associated with low  $\alpha_{\text{CO}}$  and are located in galaxy centers.

$\alpha_{\text{CO}}$  shows a factor of  $\sim 2$  standard deviation in a typical radial bin. This uncertainty can be explained primarily by the uncertainty on our  $\alpha_{\text{CO}}$  solutions themselves, which is typically close to a factor of  $\sim 2$ . It is therefore unlikely that we could predict  $\alpha_{\text{CO}}$  as a function of other variables to better precision than a factor of  $\sim 2$  unless the galaxy average  $\alpha_{\text{CO}}$  is highly correlated with that variable. In general, the galaxy averages shown in Figure 8 do not appear to be more tightly correlated with the environmental parameters. Figure 8 thus illustrates that aside from outliers at the extremes of these plots, the minimum standard deviation of  $\alpha_{\text{CO}}$  in these bins is

a factor of 2 or more and correlations with environmental parameters do not allow us to predict the behavior of  $\alpha_{\text{CO}}$  within the galaxies better than our normalized radial profile.

As previously discussed, the average profile of  $\alpha_{\text{CO}}$  versus radius is mostly flat with a central depression in some galaxies. Many of the environmental parameters we plot in Figures 8 and 9 show radial trends extending over the entire range we cover, although the normalized trends generally span less than an order of magnitude. This range does not provide the leverage to separate the dominantly radial correlations of multiple variables. Future



**Figure 9.** Normalized environmental parameters as a function of galactocentric radius  $r_{25}$ . In each panel we show the average value of each quantity in the solution pixel, normalized by the mean value for the galaxy, with gray circles. The mean and standard deviation of the binned, normalized values are shown with black circles and error bars. A linear fit is shown with a solid black line. All parameters (radiation field strength, PAH fraction, metallicity, stellar mass surface density, star-formation rate surface density, dust mass surface density and  $\alpha_{CO}$ ) show significant radial correlations. Since we have assumed radial gradients in the metallicity for many galaxies, normalized metallicity directly reflects the slopes of these gradients. In general, these radial trends are much stronger than the correlations between the variables and  $\alpha_{CO}$ , presented in Figure 8.

**Table 8**  
Correlation Properties vs.  $r_{25}$

Variable vs. $r_{25}$	Correlation <sup>a</sup> Coeff.	$\sigma$ from Null	Linear Fit	
			Offset	Slope
$\text{Log}(\alpha_{CO}/\langle\alpha_{CO}\rangle_{\text{gal}})$	+0.18	5.0	-0.10	+0.23
$\text{Log}(\bar{U}/\langle\bar{U}\rangle_{\text{gal}})$	-0.57	15.9	0.17	-0.39
$q_{\text{PAH}}/\langle q_{\text{PAH}}\rangle_{\text{gal}}$	+0.19	5.3	-0.17	+0.40
$\text{Log}(\langle\text{O}/\text{H}\rangle/\langle\text{O}/\text{H}\rangle_{\text{gal}})$	-0.65	18.2	0.07	-0.17
$\text{Log}(\Sigma_*/\langle\Sigma_*\rangle_{\text{gal}})$	-0.73	20.5	0.43	-0.97
$\text{Log}(\Sigma_D/\langle\Sigma_D\rangle_{\text{gal}})$	-0.68	19.1	0.25	-0.56
$\text{Log}(\Sigma_{\text{SFR}}/\langle\Sigma_{\text{SFR}}\rangle_{\text{gal}})$	-0.31	8.8	0.37	-0.86

**Note.** — These correlations are shown in Figure 9.

<sup>a</sup> Spearman rank correlation coefficient.

studies attempting to associate changes in  $\alpha_{CO}$  with environmental parameters will need either higher precision measurements of  $\alpha_{CO}$  or to span a greater range of environments.

One possible way to overcome the limitations of separating various radial trends is to normalize all of the variables by their mean in radial bins and then search for residual trends between them. We have investigated such non-radial variations in 0.1  $r_{25}$  bins and in general, find only very weak trends. NGC 4254 is one of few galaxies that shows a marginally significant correlation—the normalized  $\alpha_{CO}$  measurements correlate with normalized  $\bar{U}$  and  $\Sigma_*$  at the level of 4-5 $\sigma$  from the Spearman rank correlation coefficient. In both cases, the correlation is

positive, such that  $\alpha_{\text{CO}}$  increases in region with higher  $\bar{U}$  and  $\Sigma_*$  compared to the average in that radial bin. NGC 6946 also shows a correlation at  $5\sigma$  between normalized  $\alpha_{\text{CO}}$  and  $f_{\text{PDR}}$ . In this case, the correlation is negative, meaning  $\alpha_{\text{CO}}$  decreases in regions with high  $f_{\text{PDR}}$ .

NGC 6946 is unique in that the non-radial structure is clearly visible in the maps of  $\alpha_{\text{CO}}$  shown in the Appendix. The low  $\alpha_{\text{CO}}$  values in that galaxy appear to track the spiral arm structure seen in the  $I_{\text{CO}}$  and  $\Sigma_{\text{D}}$  maps. To make this observation quantitative, we have investigated the correlation between the radially normalized  $\alpha_{\text{CO}}$ ,  $I_{\text{CO}}$ ,  $\Sigma_{\text{D}}$  and  $\Sigma_{\text{HI}}$ . These correlations are weak (all are  $< 5\sigma$  significance in the Spearman rank correlation) but more widespread. NGC 3627, 4254, 4321, 5457 and 6946 all show some degree of correlation at  $> 3\sigma$  with either radially normalized  $I_{\text{CO}}$ ,  $\Sigma_{\text{HI}}$  or  $\Sigma_{\text{D}}$ . For all galaxies aside from NGC 6946, the correlations are positive, in the sense that the conversion factor is higher where there is more HI and dust or more CO emission. NGC 6946 shows negative correlations with all of these parameters.

#### 4.6.1. $\alpha_{\text{CO}}$ versus Metallicity

Metallicity has been suggested by several theoretical and observational studies to be an important driver for  $\alpha_{\text{CO}}$  variations. Unfortunately, metallicity measurements in nearby galaxies are often very uncertain and subject to systematic errors from different calibrations and techniques. In Figure 8 we show our  $\alpha_{\text{CO}}$  measurements as a function of metallicity from the PT05 calibration (middle-left panel). Our measurements span  $\sim 0.5$  dex in metallicity with no statistically significant trend in  $\alpha_{\text{CO}}$ . One possible reason for the lack of a clear trend in this figure is that we have combined metallicity measurements obtained with different techniques. In addition, many of the galaxies in our sample lack constraints on possible gradients.

To explore any metallicity trends that may be washed out due to systematic effects when combining metallicities from different sources, we isolate a sample of galaxies with uniformly determined metallicities from Moustakas et al. (2010) and plot those separately in Figure 10. We have eliminated galaxies whose metallicities have been determined from integrated spectrophotometry (those listed as “M10 Table 9” in Table 3) because the drift scan observations were not always along angles that allow a robust gradient measurement. We also isolate our highest confidence  $\alpha_{\text{CO}}$  measurements by showing only those with uncertainties less than 0.3 dex (a factor of  $\sim 2$ ). We show metallicities in both the PT05 and KK04 calibrations for comparison.

In general, there is a slight negative correlation of  $\alpha_{\text{CO}}$  with metallicity for this subsample. In the PT05 calibration, we find a rank correlation coefficient of  $r = -0.2$ , which is  $3.8\sigma$  from the null result given the number of measurements. Using KK04 metallicities, we find  $r = -0.1$  at  $2.0\sigma$  from null. If we remove the S/N cut on the  $\alpha_{\text{CO}}$  measurements, the correlations in both PT05 and KK04 essentially disappear, yielding results that are less than  $1\sigma$  from the null result.

The weakness of the correlation between  $\alpha_{\text{CO}}$  and metallicity suggest that in the regions of the galaxies we are studying, metallicity may not be the primary driver

of  $\alpha_{\text{CO}}$  variations. Along these lines, it is interesting to note the contrast between a galaxy like NGC 6946, which has a relatively shallow metallicity gradient, and galaxies like NGC 0628 and 3184 which are thought to have much steeper gradients. NGC 6946 has  $\alpha_{\text{CO}}$  spanning a range of an order of magnitude, while NGC 0628 and 3184 have much smaller ranges—the opposite of what we would expect if their metallicity gradient was the dominant factor controlling  $\alpha_{\text{CO}}$ .

#### 4.7. Properties of Full-Sample DGR Solutions

In the Appendix we show the measured DGR for all galaxies and solution pixels in figures similar to Figure 3. The DGR we report is the mean value for all of the individual sampling points in a solution pixel. Generally, the scatter in the  $\text{DGR}_i$  values within a solution pixel is small ( $< 0.1$  dex). This means that the uncertainty on the  $\alpha_{\text{CO}}$  value generally dominates the uncertainty on DGR as well. Therefore, it is important to note that the errors in the DGR and  $\alpha_{\text{CO}}$  values are highly correlated. We assign a representative uncertainty on the DGR using the  $\pm 1\sigma$  bounds on  $\alpha_{\text{CO}}$ . In general, when good solutions are obtained, the DGR measurements vary smoothly across the galaxy. This supports our key assumption that DGR varies on scales larger than our solution pixels. The smoothness of the DGR maps can be seen by inspecting the figures in the Appendix and the results for NGC 0628 shown in Figure 3.

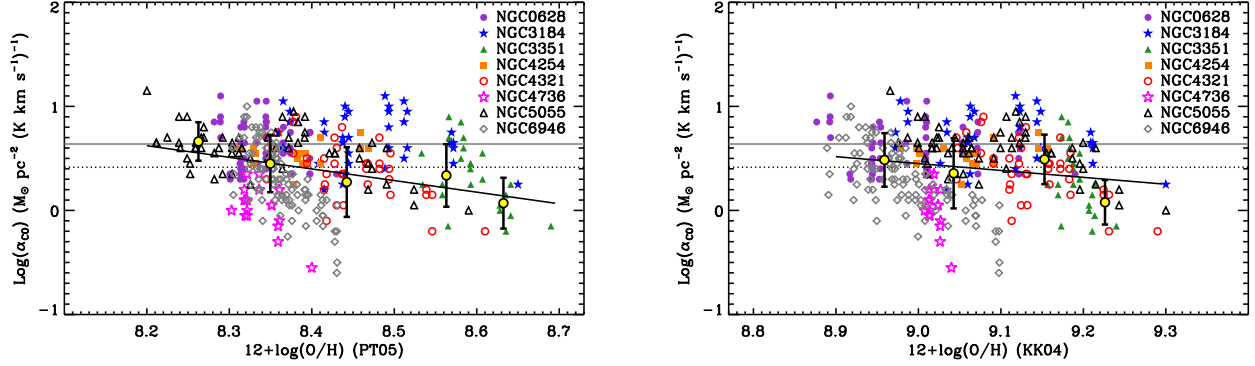
In Figure 11 we show a histogram of all of the measured DGR values for our galaxies that comply with our cuts on inclination and  $I_{\text{CO}}$ . The average of our measurements treating all lines of sight equally is  $\text{Log}(\text{DGR}) = -1.86$  with a standard deviation of 0.22 dex. This is slightly higher than the value typically adopted for the solar neighborhood of  $\text{Log}(\text{DGR}_{\text{MW}}) = -2.0$ . Forcing all galaxies to contribute equally to the average despite differing numbers of solution pixels gives  $\text{Log}(\text{DGR}) = -1.96$ . The lower scatter in the DGR measurements for all solution pixels compared to the  $\alpha_{\text{CO}}$  measurements, despite the uncertainty on  $\alpha_{\text{CO}}$  dominating the uncertainty on DGR, is due to the contribution of HI to the total gas mass surface density. Because HI makes up some fraction of the gas mass the DGR has a smaller possible range over which to vary compared to  $\alpha_{\text{CO}}$ .

#### 4.8. Correlations of DGR with Environmental Parameters and Radius

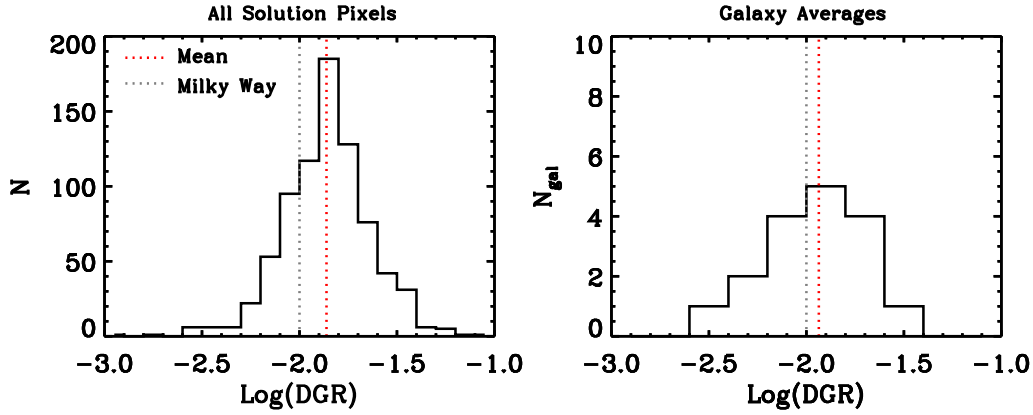
DGR may also vary as a function of environmental parameters. To explore any such trends we show our measured DGR values as a function of the same tracers we have previously studied in Figure 12. We list the correlation coefficients and linear fit parameters in Table 9.

DGR shows significant correlations with galactocentric radius, metallicity and  $\Sigma_*$ . Even with heterogeneously determined metallicities, it shows a much clearer trend with  $12+\text{log}(\text{O}/\text{H})$  than  $\alpha_{\text{CO}}$  does over the same range. A correlation of DGR with metallicity is expected—given the high depletions of elements such as Mg, Si, Ca and Ti in the local area of the Milky Way, to first order the mass of dust should be proportional to the amount of heavy elements.

In Figure 13, we show DGR as a function of metallicity for the same sample of galaxies from Figure 10. In addition to the best linear fit, shown with a dotted black line,



**Figure 10.** Measured  $\alpha_{\text{CO}}$  values as a function of metallicity for galaxies with HII region abundance gradients from Moustakas et al. (2010) in the PT05 (left) and KK04 (right) calibrations. Only measurements with uncertainties less than  $< 0.3$  dex are shown. The mean and standard deviation in 0.1 dex bins of metallicity are shown with yellow circles and black error bars. A linear fit to  $\alpha_{\text{CO}}(Z)$  is overlaid with a solid black line. The correlation of  $\alpha_{\text{CO}}$  with metallicity is weak for both calibrations. In particular it is clear that galaxies with shallow metallicity gradients like NGC 6946, can still span a wide range of  $\alpha_{\text{CO}}$  values, whereas those with large gradients, like NGC 3184, may have essentially constant  $\alpha_{\text{CO}}$ .



**Figure 11.** Histograms of the measured DGR values for all solution pixels (left) and galaxies (right) in our sample. The dotted line shows the mean value for the sample and the red line shows the local MW DGR of 0.01 for comparison. The average DGR for our sample is slightly higher than in the MW. The standard deviation of the DGR measurements is 0.22 dex, which is smaller than the scatter in the  $\alpha_{\text{CO}}$  values for these same pixels.

**Table 9**  
DGR Correlation Properties

Log(DGR) vs. Variable	Correlation <sup>a</sup> Coeff.	$\sigma$ from Null	Linear Fit <sup>b</sup>	
			Offset	Slope
$r_{25}$	-0.33	9.2	-1.71	-0.35
$\text{Log}(\bar{U})$	+0.05	1.5	-1.87	+0.02
qPAH (%)	+0.02	0.4	-1.88	+0.00
$12+\text{Log}(\text{O}/\text{H})$	+0.26	7.3	-6.50	+0.55
$\text{Log}(\Sigma_*)$	+0.28	7.9	-2.27	+0.21
$\text{Log}(\Sigma_{\text{SFR}})$	-0.07	2.1	-1.88	-0.01

**Note.** — These correlations are shown in Figure 8.

<sup>a</sup> Spearman rank correlation coefficient.

<sup>b</sup> Correlation with metallicity using a homogeneous sample of metallicity measurements is discussed in Section 4.8.

we also plot a prediction for scaling the local MW DGR linearly with metallicity (solid black line) and a factor of 2 higher and lower DGR with dashed lines. The scaling of the plot is such that it covers three orders of magnitude, the same range covered in Figure 10. It is clear that the DGR values have much less scatter than the  $\alpha_{\text{CO}}$  values over the same range of metallicity—a product of the limited allowable range of DGR set by the fact

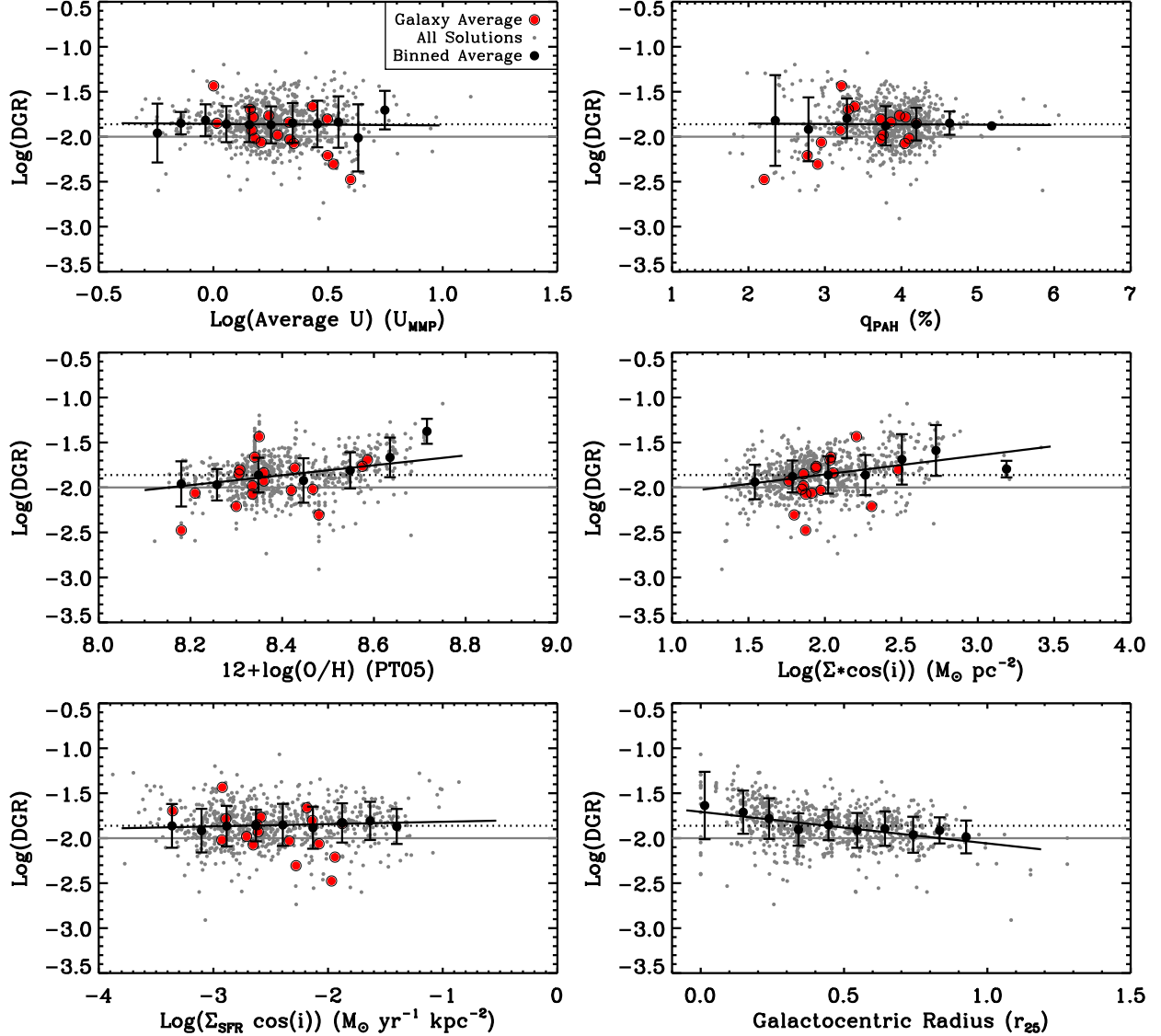
that some dust is associated with HI.

The DGR values show a stronger correlation with metallicity than the  $\alpha_{\text{CO}}$  values. In the PT05 calibration we find a rank correlation coefficient of 0.35 which is significant at  $6.4\sigma$ . For KK04, the correlation coefficient is 0.39 at  $6.9\sigma$ . In a given metallicity bin, the standard deviation of the DGR values is  $\sim 0.15$  dex for PT05 and  $\sim 0.18$  for KK04. This suggests that, on average, we should be able to predict DGR to better than a factor of 2 given the metallicity in one of these calibrations. In addition, we do not see evidence for major galaxy-to-galaxy offsets in the DGR versus metallicity plots, which distinguishes the DGR and  $\alpha_{\text{CO}}$  behavior, and most galaxies appear to have similar slopes in the plots.

Neither the KK04 nor PT05 calibration values fall directly along the line of scaled MW DGR. On the PT05 scale, almost all of our sample has higher DGR for a given metallicity than the Milky Way scaling, while the opposite is true on the KK04 scale. For purposes of scaling the local Milky Way metallicity, we have used strong-line abundance measurements calculated from the integrated spectrum of the Orion Nebula (Croxall et al, in prep).

The best linear fit to the data is shown with a dot-





**Figure 12.** DGR as a function of environmental parameters. The panels show DGR plotted versus average radiation field intensity ( $U$ ; top-left) and PAH fraction ( $q_{\text{PAH}}$ ; top-right) from the Aniano et al. (2012) fits, metallicity ( $12+\log(\text{O}/\text{H})$ ; middle-left), stellar mass surface density ( $\Sigma_*$ ; middle-right), star-formation rate surface density ( $\Sigma_{\text{SFR}}$ ; lower-left) and galactocentric radius ( $r_{25}$ ; lower-right). The solid gray line shows the Milky Way DGR and the dotted black line shows the sample average. Each individual solution above our  $\text{I}_{\text{CO}}$  and inclination cuts are shown with gray symbols. The mean and standard deviation of those values in bins are shown with black circles and error bars. A linear fit to the measurements is shown with a black line. The mean values for all galaxies are shown with red circles. DGR shows statistically significant correlations with  $r_{25}$ ,  $12+\log(\text{O}/\text{H})$  and  $\Sigma_*$ .

ted line in both the PT05 and KK04 panels. This fit is parametrized by the following equation where uncertainties have been determined using bootstrapping:

$$\text{Log}(\text{DGR}) = a - b(12 + \text{Log}(\text{O}/\text{H}) - c). \quad (4)$$

For the PT05 measurements we find the following constants:

$$\begin{aligned} a &= -1.86 \pm 0.01 \\ b &= 0.85 \pm 0.11 \\ c &= 8.39 \end{aligned}$$

For the KK04 measurements the constants are:

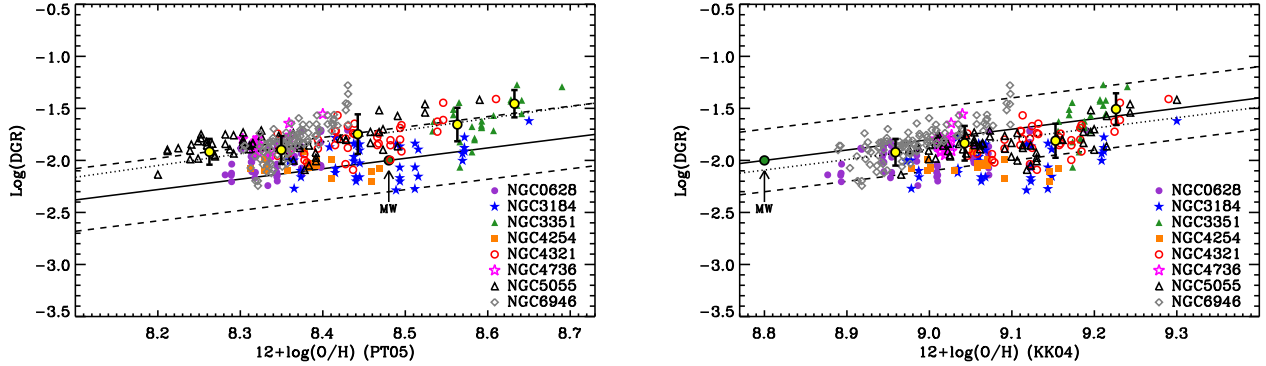
$$a = -1.86 \pm 0.01$$

$$b = 0.87 \pm 0.11$$

$$c = 9.05$$

In these equations, the constant  $c$  is the mean metallicity of the sample of points. We use this parametrization in order to avoid covariance in the offset ( $a$ ) and slope ( $b$ ). In both cases the slope is below unity. It can be seen in Figure 13 that the flatter than unity slope is mainly due to NGC 3184 (blue stars). Leaving this galaxy out of the fits produces slopes of  $1.13 \pm 0.10$  and  $1.01 \pm 0.11$  for PT05 and KK04, respectively. It also increases the significance of both correlations by  $1-2\sigma$ .

## 5. COMPARISON TO LITERATURE



**Figure 13.** Measured DGR values as a function of metallicity for galaxies with HII region abundance gradients from Moustakas et al. (2010) in the PT05 (left) and KK04 (right) calibrations. Only solutions where the uncertainty in  $\alpha_{\text{CO}}$  is less than 0.3 dex are shown, although the significance of the correlation between DGR and  $Z$  is relatively unchanged if all points are included. A linear fit to  $\text{DGR}(Z)$  is overlaid with a dotted black line. There is a clear correlation of DGR with  $Z$ . The best fit slope is slightly below linear, but if NGC 3184 is removed the correlation is consistent with linear. The solid black line shows a linear scaling of the MW DGR and metallicity, with dashed lines above and below showing a factor of 2 difference from MW. On the PT05 scale, our sample appears to have higher DGR for a given metallicity compared to the MW, while the opposite is true on the KK04 scale.

### 5.1. Measurements of $\alpha_{\text{CO}}$ in the Milky Way and Nearby Galaxies

The local region of the Milky Way is seen to have a conversion factor close to  $\alpha_{\text{CO}} = 4.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ . This standard value has been recovered to within a factor of 2 by various techniques:  $\gamma$ -ray measurements (Digel et al. 1996; Abdo et al. 2010); virial masses (Solomon et al. 1987); and dust (Dame et al. 2001; Pineda et al. 2008; Planck Collaboration et al. 2011a). A number of studies of the Galactic Center, however, have found very different answers. Using  $\gamma$ -ray observations, Strong et al. (2004) found evidence that  $\alpha_{\text{CO}}$  in the Galactic Center was factors of 5–10 lower than in the disk. Similar results using dust as a tracer for total gas mass have been found by Sodroski et al. (1995) who suggest that  $\alpha_{\text{CO}}$  is lower by factors of 3–10. Modeling of multiple  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  lines by Dahmen et al. (1998) found that the standard conversion factor from the disk overestimated molecular gas mass in the Galactic Center by an order-of-magnitude. Thus, several independent measurements suggest that the Milky Way has  $\alpha_{\text{CO}}$  near its center between 3–10 times lower than in the solar neighborhood. The properties of the transition from the standard disk value to this lower number are not well constrained although  $\gamma$ -rays provide some hint of a gradient (Strong et al. 2004).

The agreement among the various techniques in the Galactic Center provides confidence in the resulting low  $\alpha_{\text{CO}}$ . On their own, each technique is subject to a number of important systematic uncertainties. For  $\gamma$ -ray modeling, a key limitation is our knowledge of the cosmic ray distribution. In the case of multi-line modeling approaches, it is not clear that the approximations involved adequately represent the variety of excitation conditions in the molecular gas (Mao et al. 2000; Bayet et al. 2006). Virial mass based techniques rely on the assumption that the clouds are in virial equilibrium, with gravity opposed primarily by turbulent motions. If magnetic stresses and thermal pressures are significant, or if GMCs are actually not self-gravitating, the virial technique may fail to reflect the true conversion factor, particularly in regions like the Galactic Center (e.g. Dahmen et al. 1998).

Measurements of  $\alpha_{\text{CO}}$  with various techniques in nearby galaxies have provided somewhat contradictory results. Virial mass studies of GMCs in nearby galaxies tend to find  $\alpha_{\text{CO}}$  very similar to the Milky Way disk (Wilson 1995; Bolatto et al. 2008), even in galaxy centers (Donovan Meyer et al. 2012) and in low metallicity galaxies like the SMC (Bolatto et al. 2008). In contrast, a number of studies using dust-based techniques have found very high  $\alpha_{\text{CO}}$  in low-metallicity galaxies, suggesting substantial amounts of “dark molecular gas” or “CO-free  $\text{H}_2$ ” around GMCs (Israel 1997; Dobashi et al. 2008; Leroy et al. 2009b, 2011). Leroy et al. (2011) used dust to trace the total amount of gas and determine  $\alpha_{\text{CO}}$  for the major galaxies of the Local Group. Their results suggested that 1) at low metallicity,  $\alpha_{\text{CO}}$  can be well above the standard MW value, 2) in the central few kpc of M 31, the conversion factor was slightly lower than the standard value, and 3) the 10 kpc ring of M 31, M 33 and the LMC (which collectively span  $\sim 0.5$  dex in metallicity) all showed  $\alpha_{\text{CO}}$  in agreement with the MW value. Studies of the centers of several nearby galaxies with “large velocity gradient” (LVG) or related modeling have found evidence for  $\alpha_{\text{CO}}$  up to an order-of-magnitude lower than the Milky Way value (e.g. Weiß et al. 2001; Israel 2009b,a).

The study presented here is the first to create maps of  $\alpha_{\text{CO}}$  in galaxies outside the Local Group. Therefore, we are able to study  $\alpha_{\text{CO}}$  across a range of environments and connect the various trends that have been found in previous work. We find that for  $\text{I}_{\text{CO}} > 1 \text{ K km s}^{-1}$ ,  $\alpha_{\text{CO}}$  is relatively constant for a range of radii and metallicities in galaxies. In the central  $\sim \text{kpc}$ , we observe that galaxies often show a lower than average  $\alpha_{\text{CO}}$ , sometimes by up to factors of 10. These low  $\alpha_{\text{CO}}$  values we find in several galaxy centers are not unprecedented, given the results from multi-line modeling studies and the evidence that the Galactic Center shows a similar depression. Our lowest metallicities are still above the transition abundance seen by Leroy et al. (2011) where galaxies in the Local Group began to display much higher  $\alpha_{\text{CO}}$  (i.e.  $12+\text{Log}(\text{O}/\text{H}) \lesssim 8.2$ ). The picture that emerges from the synthesis of these literature results is one where  $\alpha_{\text{CO}}$  is generally around the standard MW value with a

factor of  $\sim 2$  variability in the disks of galaxies, in the regime where CO is bright and metallicity is greater than  $\sim 1/2 Z_{\odot}$ , with some galaxies showing lower  $\alpha_{\text{CO}}$  in their central kpc.

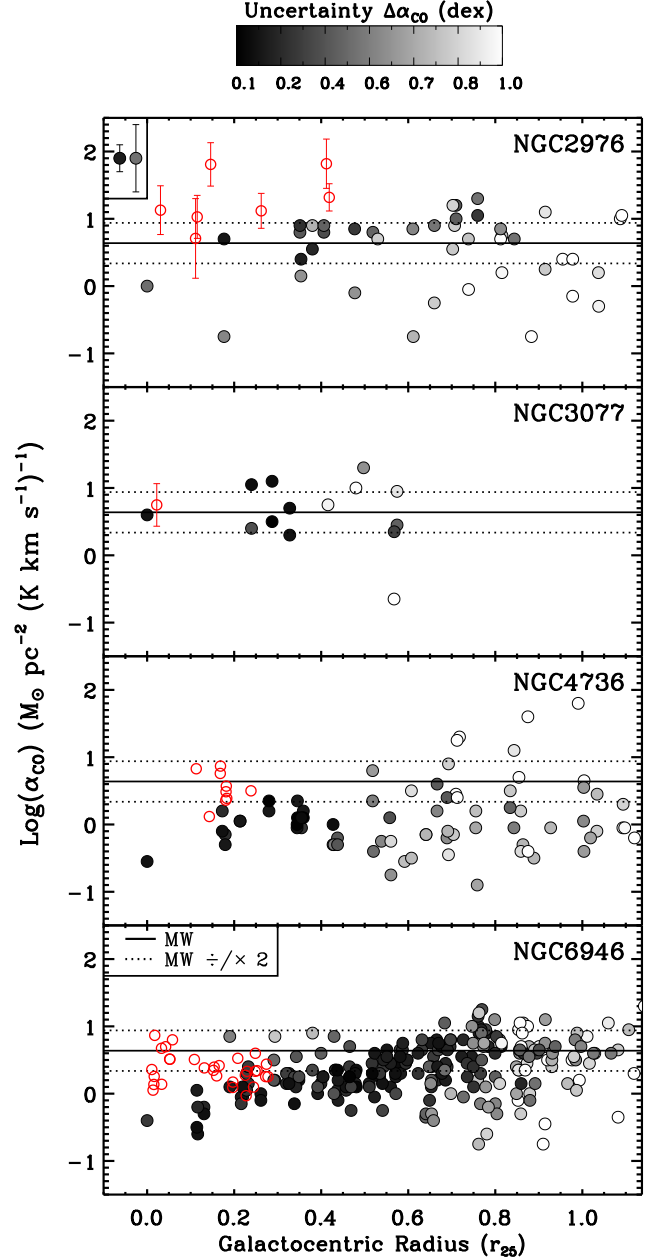
### 5.2. Direct Comparison of $\alpha_{\text{CO}}$ with Virial Mass Measurements

In several cases, our  $\alpha_{\text{CO}}$  measurements overlap with previous  $^{12}\text{CO}$  J=(1–0) virial mass based studies. Bolatto et al. (2008) derived GMC properties and virial masses for NGC 2976 and 3077. Their results for NGC 3077 are in good agreement with previous studies by Meier et al. (2001) and Walter et al. (2002). Recently, Donovan Meyer et al. (2012) and Donovan Meyer et al. (in prep) have made  $\alpha_{\text{CO}}$  determinations in the central regions of NGC 6946 and 4736, respectively, using virial masses. In Table 10 we provide a summary of the galaxies in our sample with existing literature measurements. Figure 14 shows a comparison between these literature virial mass based  $\alpha_{\text{CO}}$  measurements with what is derived in this study. In almost all cases we find a lower  $\alpha_{\text{CO}}$  using the dust-based technique than the virial mass technique.

For NGC 2976, Bolatto et al. (2008) found conversion factors  $\sim 4$  times larger than the Milky Way value on average. Almost all of our measurements for NGC 2976 have  $\alpha_{\text{CO}}$  consistent with the Milky Way value within their uncertainties. The central solution pixel has  $\alpha_{\text{CO}}$  a factor of 4–5 below the Milky Way value. In contrast, the virial mass and dust based techniques are in agreement for NGC 3077, both returning a conversion factor consistent with the Milky Way. The center of NGC 6946 stands out in our study as places with particularly low  $\alpha_{\text{CO}}$ . However, virial mass measurements find  $\alpha_{\text{CO}}$  more consistent with the Milky Way value. Figure 14 illustrates that the discrepancy decreases with radius for NGC 6946—many of the points with galactocentric radii closer to  $r_{25} \sim 0.2$  agree with our dust-based measurements. We will discuss the discrepancy between the virial and dust-based  $\alpha_{\text{CO}}$  values in the galaxy centers further in Section 6.3. It is interesting to note that the normalcy of NGC 3077, currently undergoing a starburst, compared to the also highly star-forming centers of 4736 and 6946, suggests that conditions other than just high star-formation surface density must contribute to determining  $\alpha_{\text{CO}}$ .

### 5.3. Direct Comparison with Multi-Line Modeling Techniques

The center of NGC 6946 has been observed extensively in molecular gas lines and modeled in a variety of ways. Israel & Baas (2001) modeled  $^{12}\text{CO}$  and  $^{13}\text{CO}$  lines plus [C I] (492 GHz) observations and found a conversion factor  $\sim 10$  times lower than the Milky Way value in the center. Using LVG modeling of multiple CO isotopomers including  $^{12}\text{C}^{18}\text{O}$ , Walsh et al. (2002) found a conversion factor 4–5 times below the Milky Way value. Similarly, Meier & Turner (2004) used an LVG analysis of  $\text{C}^{18}\text{O}$  observations, in addition to multiple CO lines, to argue that the central region had a conversion factor 4 times below the Milky Way value. All of these studies suggest a central  $\alpha_{\text{CO}}$  between 4–10 times lower than the Milky Way value, in good agreement with what we observe with dust, but in contrast with the virial mass results.



**Figure 14.** A comparison between virial mass-based measurements of  $\alpha_{\text{CO}}$  from the literature (shown with red circles) and the results of this study. The gray-scale color table for the points from this study shows the uncertainty on each  $\alpha_{\text{CO}}$  measurement, as in Figure 4. Sample error bars for comparison with the gray-scale color table are shown in the top left corner of the plot. Virial mass  $\alpha_{\text{CO}}$  measurements for NGC 2976 and 3077 are taken from Bolatto et al. (2008). Measurements for NGC 4736 and 6946 are from Donovan Meyer et al (in prep) and Donovan Meyer et al. (2012), respectively. For all of the targets, except NGC 3077, there is a discrepancy between the virial mass and dust based  $\alpha_{\text{CO}}$ . At larger radii, the two measurements are in better agreement in NGC 6946.

Several other galaxies in our sample have been modeled with multi-line techniques, however they are at high inclination and therefore do not have reliable  $\alpha_{\text{CO}}$  measurements from our work. Israel (2009b) used multiple  $^{12}\text{CO}$  and  $^{13}\text{CO}$  lines plus [C I] (492 GHz) observations towards the central region of NGC 4631 to constrain  $\alpha_{\text{CO}}$

**Table 10**  
Literature  $\alpha_{\text{CO}}$  Measurements

Galaxy	Regan et al. (2001) Central Excess?	$3\sigma$ Below MW $\alpha_{\text{CO}}$ (this study)	Literature $\alpha_{\text{CO}}$ Measurements	
			Type	Reference
NGC 0628	N	N		
NGC 2976	...	N	VM	B08
NGC 3077	...	N	VM	B08
NGC 3351	Y	Y		
NGC 3521	N	N		
NGC 3627	Y	Y		
NGC 4321	Y	Y		
NGC 4631	...	N	ML	I09
NGC 4736	Y	Y	VM	DM12b
NGC 5055	Y	N <sup>a</sup>		
NGC 6946	Y	Y	VM, ML	DM12a, IB01, MT04, W02
NGC 7331	N	N	ML	IB99

**References.** — B08 - Bolatto et al. (2008); DM12a - Donovan Meyer et al. (2012); DM12b - Donovan Meyer et al. (in prep); I09 - Israel (2009b); IB99 - Israel & Baas (1999); IB01 - Israel & Baas (2001); M01 - Meier et al. (2001); MT04 - Meier & Turner (2004); R01 - Regan et al. (2001); W02 - Walsh et al. (2002)

**Note.** — VM - virial mass; ML - multi-line modeling.

<sup>a</sup> 2.6 $\sigma$  below MW  $\alpha_{\text{CO}}$ .

and found a value 6 times lower than the standard Milky Way value. Similarly, Israel & Baas (1999) argued for  $\alpha_{\text{CO}} \sim 5$  times lower than the Milky Way value in the center of NGC 7331. In both of these highly inclined galaxies we find  $\alpha_{\text{CO}}$  a factor of 2 or more higher than the MW  $\alpha_{\text{CO}}$ . This is due to the failure of our technique at high inclinations.

#### 5.4. Comparison with CO Exponential Disk Profiles

Regan et al. (2001) found that approximately half of their sample of galaxies observed in the BIMA SONG survey show excess CO emission in their centers compared to the extrapolation of their best fit exponential disk profile. They argued that this could be due to enhanced reservoirs of molecular gas in the centers or a change in the conversion factor. Table 10 lists the central excess classification for the galaxies in our sample studied by Regan et al. (2001). Indeed, we find that in every case where they found excess CO above the exponential profile, we find a conversion factor significantly below the Milky Way value. Conversely, for the three galaxies we have observed and that they found to *not* have an excess, we find conversion factors consistent with the Milky Way value or slightly higher. Similar results are found when comparing with the radial profiles determined from the HERACLES CO maps we utilize in this study (see radial profiles in Schruba et al. 2011). In general, the offset between the central  $\alpha_{\text{CO}}$  and galaxy average  $\alpha_{\text{CO}}$  from our measurements is similar in magnitude to the excess observed at the centers compared to the extrapolated exponential disk profile.

## 6. DISCUSSION

### 6.1. Drivers of $\alpha_{\text{CO}}$ Variations

In the following, we explore the correlations or lack thereof between  $\alpha_{\text{CO}}$  and parameters that may influence it. Since our resolution elements are large compared to an individual GMC, our  $\alpha_{\text{CO}}$  value is an average over a population of GMCs, including any molecular gas that may be in a more diffuse phase and not in self-gravitating clouds.

For an individual, self-gravitating, turbulence-supported molecular cloud, there are several key parameters that influence  $\alpha_{\text{CO}}$ : the density and temperature of the gas and the fraction of the mass that exists in the “CO-dark” phase (where  $\text{H}_2$  self-shields and CO is photodissociated). The general dependence of  $\alpha_{\text{CO}}$  on density and temperature can be illustrated using a simple model—a spherical, homogeneous cloud where self-gravity is opposed primarily by turbulence and  $^{12}\text{CO}$  J=(1–0) is optically thick. Following the derivation in Draine (2011),

$$\alpha_{\text{CO}} = 3.4n_3^{0.5}(e^{5.5/T_{\text{ex}}} - 1) \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}. \quad (5)$$

Here,  $n_3$  is the H nucleon density  $n_H = 10^3 n_3 \text{ cm}^{-3}$  and  $T_{\text{ex}}$  is the excitation temperature. Real molecular clouds are certainly not spherical and homogenous, but this model allows us to understand the basic dependence of  $\alpha_{\text{CO}}$  on density and temperature (note that simulated molecular clouds with non-spherical, non-homogenous structure show similar basic scalings; Shetty et al. 2011). Molecular clouds with increased density will have higher  $\alpha_{\text{CO}}$  while clouds with increased temperature have lower  $\alpha_{\text{CO}}$ .

Because CO is optically thick at solar metallicity, the abundance of C or O does not directly influence  $\alpha_{\text{CO}}$ . However, metallicity may indirectly influence  $\alpha_{\text{CO}}$  by altering the density or temperature structure of the gas, since the heating and cooling rates may be affected by metallicity or correlate with metallicity. At lower metallicities, the transition between ionized and neutral carbon to CO may shift relative to the HI/ $\text{H}_2$  transition due to a lack of dust shielding, leading to layers of “CO-dark”  $\text{H}_2$  (Tielens & Hollenbach 1985; van Dishoeck & Black 1988; Wolfire et al. 1993; Kaufman et al. 1999; Bell et al. 2006).  $\alpha_{\text{CO}}$  will increase when there are significant amounts of gas in these layers. Recent work by Wolfire et al. (2010) used PDR modeling and a spherical model for a turbulent molecular cloud to study variations in the conversion factor. They find that the “dark molecular gas” fraction (i.e. the fraction of the molecular cloud mass where  $\text{H}_2$  exists but CO is photodissociated) depends primarily on the extinction through the cloud or

DGR. Studies of simulated molecular clouds have also found a dependence of  $\alpha_{\text{CO}}$  on extinction through the cloud (Glover & Mac Low 2011).

The simple model we have described above assumes that the cloud’s self-gravity is balanced by turbulence. If there are other forces that contribute to the virial equation,  $\alpha_{\text{CO}}$  may be altered. For a self-gravitating cloud, an increase in the pressure on the surface of the cloud will lead to a larger velocity dispersion. Because CO is optically thick, the amount of emission that “escapes” in the CO line is directly tied to the velocity dispersion of the cloud and increasing the velocity dispersion increases the CO emission for the same mass of  $\text{H}_2$ . Therefore, if a self-gravitating cloud were subject to significant external pressure we would expect a lower  $\alpha_{\text{CO}}$ . Conversely, if magnetic fields played an important role in supporting the cloud, this would lower the velocity dispersion and raise  $\alpha_{\text{CO}}$ . In ultra-luminous infrared galaxies (ULIRGs), the molecular gas may not be in individual self-gravitating clouds, but instead in a large-scale molecular medium where stellar mass contributes to the gravitational potential. (e.g. Downes & Solomon 1998). In this case, the velocity dispersion is larger than what would be expected from the gas mass alone and the CO emission is enhanced for a given gas mass (resulting in a lower  $\alpha_{\text{CO}}$ ).

In a  $\sim\text{kpc}$  region of a galaxy, many individual molecular clouds will be averaged together in our measurement. Therefore, another factor which could contribute to the variation of our measured  $\alpha_{\text{CO}}$  is changes in the cloud populations. In addition, any significant component of diffuse CO emission would be included as well. Several studies have suggested that CO emission from diffuse gas may not be negligible, even in the local area of the Milky Way (Liszt & Lucas 1998; Goldsmith et al. 2008). Interestingly, it appears that for the Milky Way,  $\alpha_{\text{CO}}$  is similar in diffuse molecular gas and self-gravitating GMCs (Liszt et al. 2010). However, it is possible that under differing environmental conditions the conversion factors appropriate for these two types of gas could be quite different. The contribution of diffuse molecular gas with a different  $\alpha_{\text{CO}}$  has been cited previously as a cause for discrepancies between different techniques for measuring  $\alpha_{\text{CO}}$  in M 51 (Schinnerer et al. 2010).

To summarize our theoretical expectations,  $\alpha_{\text{CO}}$  measured in  $\sim\text{kpc}$  regions of nearby galaxies can vary as a function of environment for many reasons: changes in the excitation temperature and density of the gas or contributions from pressure or magnetic support in self-gravitating clouds; envelopes of “CO-dark” gas; changes in the molecular cloud population; or contributions from diffuse CO emission. Unfortunately, directly measuring temperature, density and velocity dispersion in large samples of extragalactic GMCs is challenging due to the need to resolve individual clouds in multiple molecular gas emission lines. Therefore, we are left with more indirect tracers of potential changes to the GMC properties. In Section 4.6 we examined the correlation of  $\alpha_{\text{CO}}$  with  $\bar{U}$ ,  $q_{\text{PAH}}$ , metallicity,  $\Sigma_*$ ,  $\Sigma_{\text{SFR}}$ ,  $\Sigma_{\text{D}}$  and galactocentric radius.

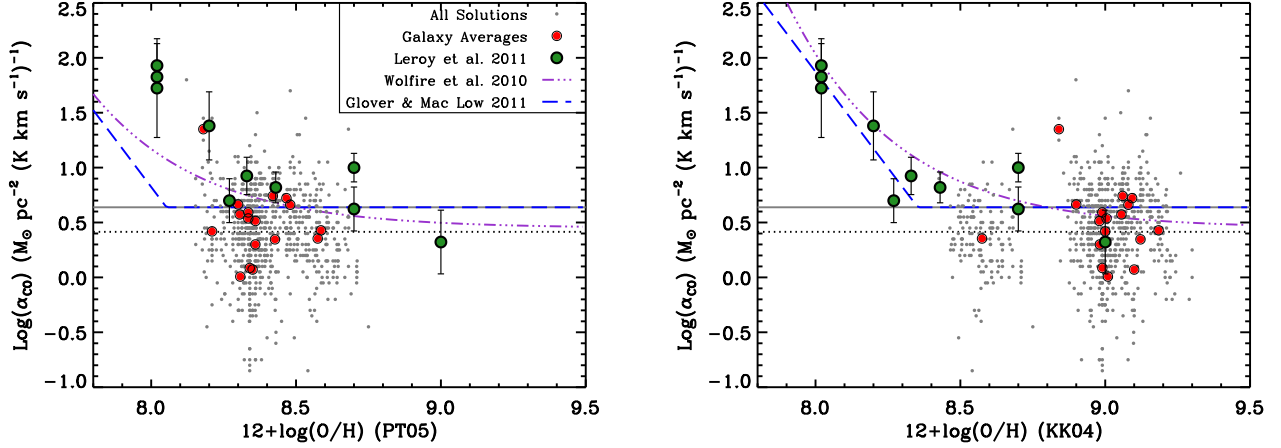
The average radiation field  $\bar{U}$  could influence  $\alpha_{\text{CO}}$  through the gas excitation temperature. If photoelectric heating dominates over other heat sources (e.g. cosmic rays) at the  $\tau_{\text{CO}} \sim 1$  surface, then the intensity of the ra-

diation field may play a role in determining  $T_{\text{ex}}$  (Wolfire et al. 1993). Likewise,  $q_{\text{PAH}}$  and metallicity could both potentially influence the efficiency of the photoelectric effect (Bakes & Tielens 1994; Röllig et al. 2006), thereby changing the heating rate. We expect that  $\Sigma_{\text{SFR}}$  should be responsible for higher  $\bar{U}$  in many regions. Enhanced SFR leading to higher radiation field intensities has been suggested as the explanation for high observed  $\alpha_{\text{CO}}$  in several outer-disk molecular clouds in M 33 (Bigiel et al. 2010). If the gas excitation temperature were affected by the radiation field or photoelectric heating, we would expect negative correlations (i.e. lower  $\alpha_{\text{CO}}$  at higher  $\bar{U}$ ,  $\Sigma_{\text{SFR}}$ ,  $q_{\text{PAH}}$ , etc). The correlations we observe between  $\alpha_{\text{CO}}$  and  $\bar{U}$ ,  $q_{\text{PAH}}$  and  $\Sigma_{\text{SFR}}$  are generally weak.  $\bar{U}$  and  $\alpha_{\text{CO}}$  show the strongest association and the slope of the trend is negative, with lower  $\alpha_{\text{CO}}$  at higher  $\bar{U}$ . This is potentially consistent with the expectation of higher radiation field intensities leading to warmer molecular gas temperatures, but the correlation is weak and other variables may play a more important role.

We see a weak trend of  $\alpha_{\text{CO}}$  with metallicity. Since our observations are limited to regions with metallicities similar to or higher than the Milky Way, we may not expect to see a strong correlation between  $\alpha_{\text{CO}}$  and metallicity. The fraction of gas mass in the layer where CO is photodissociated is predicted to be  $\sim 30\%$  at Milky Way metallicity/DGR (Wolfire et al. 2010). Thus, increasing the DGR should only have a minimal effect on the conversion factor at MW metallicity and above. To illustrate this point, in Figure 15 we plot our  $\alpha_{\text{CO}}$  measurements as a function of metallicity and overlay the Leroy et al. (2011) Local Group measurements and the models of Wolfire et al. (2010) and Glover & Mac Low (2011). The model predictions are normalized to have  $\alpha_{\text{CO}} = 4.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  at the MW metallicity (i.e.  $12 + \text{Log}(\text{O}/\text{H}) = 8.5$  in PT05 and 8.8 in KK04; Croxall et al., in prep). Both models assume a linear scaling of DGR with metallicity and a fixed gas mass surface density for molecular clouds. The model predictions are discussed in detail in Leroy et al. (submitted). In both calibrations, our measurements do not extend into the regime where “CO-dark”  $\text{H}_2$  dominates  $\alpha_{\text{CO}}$ . We note that an investigation of the  $\alpha_{\text{CO}}$ -DGR relationship using our results would require taking into account the strong correlation of the uncertainties in these parameters.

The strongest correlation we observe for  $\alpha_{\text{CO}}$  is that with  $\Sigma_*$ . This correlation is the only one that is stronger than the correlation of  $\alpha_{\text{CO}}$  with galactocentric radius  $r_{25}$ . In essence, our definition of  $r_{25}$  is based on a scale length of the stellar disk, defined by a B-band surface brightness, so it is possible the stronger correlation of  $\alpha_{\text{CO}}$  with  $\Sigma_*$  is due to it being a better proxy for the disk scale length than  $r_{25}$ . In addition, of the environmental parameters we have available for our analysis,  $\Sigma_*$  is the most straightforward to measure and may show the smallest systematic uncertainties. It may be the strongest correlation simply because the other parameters are more uncertain. The question remains, however, as to why  $\alpha_{\text{CO}}$  would correlate with the stellar mass surface density. There are a number of possibilities: pressure contributions to GMC virial balance, enhanced fractions of diffuse CO emission correlated with ISM pressure, changes to the population of GMCs, or other effects.





**Figure 15.**  $\alpha_{\text{CO}}$  as a function of metallicity compared to previous measurements and models. The left panel shows measurements in the PT05 calibration while the right panel shows KK04. Measurements from this paper are shown with gray points (individual solutions) and red circles (galaxy averages). We show all of the solution pixels where  $I_{\text{CO}} > 1 \text{ km s}^{-1}$  and  $i > 65^\circ$ , regardless of the source of the metallicity measurement (i.e. without the requirement of having measured HII region metallicities from M10). Measurements of  $\alpha_{\text{CO}}$  in Local Group galaxies from Leroy et al. (2011) are shown with green circles. The MW  $\alpha_{\text{CO}}$  is shown with a gray line and the average of our solution pixels with no weighting is shown with a dotted black line. Predictions based on the model of Wolfire et al. (2010) are shown with a purple dot-dashed line and those based on Glover & Mac Low (2011) are shown with a dashed blue line. These predictions assume a linear dependence of DGR on metallicity and a fixed gas mass surface density for molecular clouds of  $\Sigma_{\text{GMC}} = 100 \text{ M}_\odot \text{ pc}^{-2}$ . The model predictions are normalized to have  $\alpha_{\text{CO}} = 4.4 \text{ M}_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  at the metallicity adopted for the Milky Way in each calibration. Note that the metallicities we use for NGC 5457 are not from strong line calibrations, so it appears in the same position both plots. Regardless of the metallicity calibration, our measurements do not extend to low enough metallicities to constrain the effects of “CO-dark”  $\text{H}_2$ .

We do not speculate here about what causes this correlation, only note that observations of multiple molecular gas lines at GMC resolution will help understand these trends and are possible with ALMA.

Although we see some evidence for weak correlations between  $\alpha_{\text{CO}}$  and environmental variables, our primary result is that in regions with  $I_{\text{CO}} > 1 \text{ km s}^{-1}$  in these galaxies,  $\alpha_{\text{CO}}$  is mostly insensitive to environment except in the central regions. This may be due to our limited S/N for each individual  $\alpha_{\text{CO}}$  measurement plus the relatively small range of environmental conditions we probe. Another possibility is that in the disks of most galaxies, the properties of molecular gas are insensitive to environment because most of the gas resides in molecular clouds that are not under significant external pressure or subject to enhanced turbulence or magnetic fields. The conversion factor appropriate for such clouds should be similar to the standard Milky Way value.

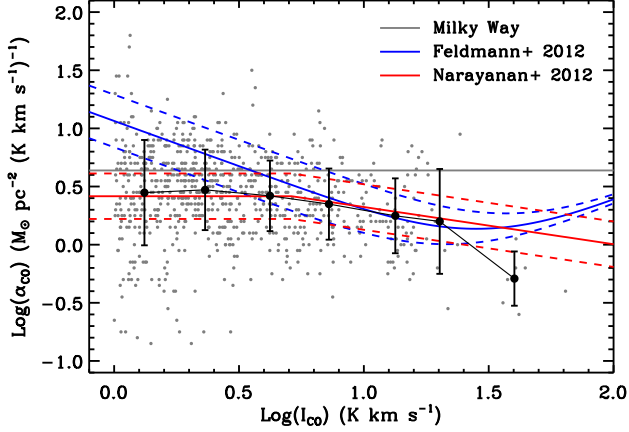
## 6.2. Comparison with Galaxy Simulations

Because of the resolution of our observations, our measurements average over a population of molecular clouds. This means that environmental variations in the cloud population can also be responsible for changes in  $\alpha_{\text{CO}}$ . Therefore, it is interesting to compare our results to what has been found with galaxy simulations, despite the fact that these simulations are forced to adopt a sub-grid model that prescribes  $\alpha_{\text{CO}}$  for unresolved clouds. In Figure 16 we show our measured  $\alpha_{\text{CO}}$  values as a function of the average  $I_{\text{CO}}$  in each solution pixel. Due to our completeness cut, we have no points below  $1 \text{ K km s}^{-1}$ . The mean and standard deviation of the  $\alpha_{\text{CO}}$  measurements in bins of  $0.25 \text{ K km s}^{-1}$  are shown with black circles and error bars.

Overlaid on Figure 16 we show the predictions of two recent simulations. Feldmann et al. (2012, F12) cou-

ples full galaxy simulations with the Glover & Mac Low (2011) cloud-based conversion factor predictions assuming a fixed gas temperature and either a constant line width of  $3 \text{ km s}^{-1}$  or a virial scaling. The Narayanan et al. (2012, N12) predictions include sub-grid semi-analytic models for the chemical and thermal state of the gas and dust. In the N12 models, the temperature of the molecular gas is not fixed and depends on heating by cosmic rays and, in dense regions, on energy transfer with dust. For both models it is necessary to adopt a filling factor or clumping correction due to the difference in resolution between the simulations and our observations. F12 and N12 both have  $\sim 60 - 70 \text{ pc}$  resolution, so we apply the same correction to both. For purposes of comparing with the trend of our observed  $\alpha_{\text{CO}}$  as a function of CO integrated intensity, we have adopted a filling factor correction of 3. This correction factor is larger than purely the ratio of the resolutions because our beam will contain more than one molecular cloud. Verifying that this absolute scaling is correct would require a more detailed investigation that is beyond the scope of this paper.

We find that the predicted trend of  $\alpha_{\text{CO}}$  with CO integrated intensity from Narayanan et al. (2012) matches the average observed behavior well, aside from underpredicting  $\alpha_{\text{CO}}$  in the central regions of some galaxies. There is considerable scatter around this trend, however. The Feldmann et al. (2012) results diverge from our measured trend at low CO integrated intensities, predicting a steeper increase than we observe. Feldmann et al. (2012) argue that on  $\sim \text{kpc}$  scales metallicity is the primary driver of the conversion factor variations. This metallicity dependence reflects, to first order, the Glover & Mac Low (2011) dependence between  $\alpha_{\text{CO}}$  and extinction through the cloud with the addition that Feld-



**Figure 16.** A comparison between our  $\alpha_{\text{CO}}$  measurements and the predictions of simulations by Narayanan et al. (2012) and Feldmann et al. (2012). On the x-axis we show the average  $I_{\text{CO}}$  in a given solution pixel. All solutions above our  $I_{\text{CO}}$  and inclination cuts are shown as gray circles. The simulation predictions are shown at three possible metallicities:  $Z = Z_{\odot}$  in a solid line and a factor of 2 above and below that with dashed lines. The mean and standard deviation in  $0.25 \text{ K km s}^{-1}$  bins are shown with black circles and error bars. The predictions from the simulations have been divided by a filling factor of 3 to correct for our different resolutions. In general, the average behavior of our  $\alpha_{\text{CO}}$  measurements agrees well with the predictions of the Narayanan et al. (2012) model except at the highest  $I_{\text{CO}}$ .

mann et al. (2012) assume a metallicity dependent DGR. Our  $\alpha_{\text{CO}}$  results do not show a strong dependence on metallicity, in contrast to this prediction. One key issue may be the assumption of a fixed gas temperature in the clouds. Narayanan et al. (2012) do not make such an assumption and see a decrease in  $\alpha_{\text{CO}}$  in regions with high star-formation rate surface densities due to enhanced gas temperatures and velocity dispersions.

### 6.3. Low Central $\alpha_{\text{CO}}$ and Discrepancies with Virial Mass Based Measurements

For some galaxy centers in our sample we measure  $\alpha_{\text{CO}}$  lower than the typical Milky Way value by factors of 5–10. Interestingly, the virial mass based  $\alpha_{\text{CO}}$  measurements for several of these regions do not agree with the values found here, instead recovering  $\alpha_{\text{CO}}$  values close to that of the Milky Way. Results of multi-line modeling are generally in much better agreement with our results. These centers also tend to be regions where the CO shows an excess over the exponential disk, as found by Regan et al. (2001). From Figure 14 we found that the discrepancy between virial mass and dust-based  $\alpha_{\text{CO}}$  decreases with radius for NGC 6946—suggesting that this is a property of the galaxy centers rather than an issue with the resolution of the virial mass techniques (which tends to be comparable to the size of the GMCs).

There are several scenarios in which  $\alpha_{\text{CO}}$  may decrease but the virial mass based  $\alpha_{\text{CO}}$  would appear similar to the MW value. If the molecular gas is in self-gravitating GMCs, it is possible to decrease  $\alpha_{\text{CO}}$  by increasing the velocity dispersion of the cloud due to the effect of external pressure. In such a situation, the measured line-width would lead to a larger virial mass and the cloud’s CO luminosity would also increase. Thus, by comparing the virial mass and CO luminosity of more highly pressurized clouds, one could derive a conversion factor similar to the

MW value, driven by the fact that the virial mass has overestimated the true  $\text{H}_2$  mass. Oka et al. (1998a) have suggested that external pressure in the Galactic Center can account for up to an order-of-magnitude change in the conversion factor. However, Donovan Meyer et al. (2012) found that GMCs in NGC 6946 did not generally show enhanced velocity dispersion, in contrast to the Galactic Center clouds identified by Oka et al. (1998b).

Another potential explanation for this discrepancy is that gas in the centers of some galaxies is not in self-gravitating GMCs, but rather in a larger-scale molecular medium that is gravitationally bound to the stars and gas. In this situation, the velocity dispersion is larger than would be the case for self-gravity of the gas alone, and more CO emission is produced for a given amount of gas. This explanation has been suggested by Downes et al. (1993) and Downes & Solomon (1998) to explain the properties of molecular gas in the nuclear disks of ultra-luminous infrared galaxies (ULIRGs) (see also recent work by Papadopoulos et al. 2012).

These scenarios should alter the velocity dispersion, temperature and optical depth of the molecular gas. With the resolution of the available data, we cannot obtain reliable measurements of velocity dispersion in the galaxy centers. Each resolution element encompasses a range of velocities purely due to rotation, so we cannot disentangle dispersion from rotation. The resolution is also far too low to isolate individual GMCs. We do have some hope of testing predictions about the optical depth and temperature by examining the ratios of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  lines. Usero et al. (in prep) presents measurements of  $^{13}\text{CO}$  and  $^{12}\text{CO}$  lines towards regions of several HERACLES galaxies. Selecting all of their pointings towards the disks of galaxies in our sample (in regions above our  $I_{\text{CO}}$  and inclination cuts), the uncertainty weighted mean of  $R_{12/13} = ^{12}\text{CO J}=(1-0)/^{13}\text{CO J}=(1-0)$  is  $8.24 \pm 0.11$ . The only galaxy centers with  $^{13}\text{CO}$  measurements are NGC 0628, 3184, 5055 and 6946. NGC 0628, 3184 and 5055 show  $R_{12/13}$  consistent with or slightly lower than the average disk value. NGC 6946, on the other hand, has  $R_{12/13} = 18.53 \pm 0.81$ . The high  $R_{12/13}$  for the center of NGC 6946 has been noted in several previous studies (Paglione et al. 2001; Israel & Baas 2001; Meier & Turner 2004). Of those four galaxies, NGC 6946 is the only one with a central  $\alpha_{\text{CO}}$  more than  $3\sigma$  below the MW value. Further attempts to explain the low  $\alpha_{\text{CO}}$  values in some galaxy centers will require more extensive mapping in other molecular gas lines, preferably at high spatial resolution.

### 6.4. Dust-to-Gas Ratio

As shown in Figures 12 and 13, we observe a good correlation of DGR with metallicity. Unlike most previous studies of DGR resolved within galaxies, we made no assumption about  $\alpha_{\text{CO}}$  in determining these values. Although we do not probe a wide range of metallicity due to the limitations on CO S/N, it is clear in Figure 13 in particular, that DGR is correlated with metallicity with less than a factor of 2 scatter over 0.5 dex in metallicity. A linear dependence of DGR on metallicity suggests a constant fraction of heavy elements are locked up in dust grains. Chemical evolution and dust life-cycle models have varying predictions for the dependence of DGR

on metallicity (Dwek 1998; Lisenfeld & Ferrara 1998; Hirashita et al. 2002). Most of the dramatic differences between the models, however, occur at lower metallicities and observations of dwarf galaxies may provide more leverage on distinguishing between models (e.g. Herrera-Camus et al. 2012).

### 6.5. Recommendations on Choosing $\alpha_{\text{CO}}$

Due to the requirements on CO S/N to apply the technique we have used, our measurements only tell us about  $\alpha_{\text{CO}}$  above  $I_{\text{CO}}=1 \text{ K km s}^{-1}$  in the galaxies we have targeted. Generally, this limits us to the inner parts of galaxies ( $< r_{25}$ ) where metallicities are comparable to the MW disk. However, these are the regions where  $\text{H}_2$  contributes most significantly to the total gas mass (Schruba et al. 2011), so applying our conversion factor results to unresolved galaxies should work reasonably well for recovering the total  $\text{H}_2$  mass. A forthcoming paper extending our study to the HI dominated regions of the KINGFISH galaxies, will test this assertion. Note that our recommendations are only applicable to spiral galaxies with metallicity similar to that of the MW.

For an unresolved galaxy, we recommend adopting our galaxy-based average  $\alpha_{\text{CO}}$  of  $3.1 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  with uncertainty of 0.3 dex (a factor of  $\sim 2$ ). This is the mean and standard deviation of the average value for all galaxies with inclination less than  $65^\circ$ .

In dealing with resolved galaxies, we recommend adopting a flat radial  $\alpha_{\text{CO}}$  profile for regions with  $I_{\text{CO}} > 1 \text{ K km s}^{-1}$  except in the central  $\sim 0.1 r_{25}$ , where the average  $\alpha_{\text{CO}}$  is a factor of 2 lower. When dealing with a single galaxy, our average radial profile from Figure 7 suggest that the  $\alpha_{\text{CO}}$  values have  $\sim 0.2$  dex of scatter in each radial bin (0.3 dex for the central bin). Therefore, for studies of molecular gas within a single galaxy, the relative values of  $\alpha_{\text{CO}}$  adopted from this profile have a factor of  $\sim 1.5$  uncertainty. When comparing resolved galaxies, it is necessary to further recognize that the absolute normalization of the radial profiles, i.e. the galaxy average value, has an additional 0.3 dex of uncertainty.

In the case where additional information about the galaxy is available, such as profiles of stellar mass surface density, star formation rate surface density or line ratios of  $^{12}\text{CO} (2-1)/(1-0)$  or  $^{12}\text{CO}/^{13}\text{CO}$ , we suggest using these maps to pick out regions that may have  $\alpha_{\text{CO}}$  very different from the mean. This includes regions with  $\Sigma_* \gtrsim 1000 \text{ M}_{\odot} \text{ pc}^{-2}$ ,  $\Sigma_{\text{SFR}} \gtrsim 0.1 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ , or  $R_{21} \gtrsim 1$  at our working resolution of  $\sim 1 \text{ kpc}$ . In these regions,  $\alpha_{\text{CO}}$  can be 5–10 times lower than the MW  $\alpha_{\text{CO}}$ , and are often systematically lower than the average radial profile.

## 7. SUMMARY & CONCLUSIONS

The availability of high angular resolution far-infrared maps from the *Herschel* Space Observatory and sensitive  $^{12}\text{CO} \text{ J}=(2-1)$  and HI maps has recently allowed us to trace dust and gas mass surface densities in nearby galaxies on  $\sim \text{kpc}$  scales. On these scales, we expect (and have verified) that the DGR is approximately constant. Therefore, we are able to combine the dust mass surface density maps with matched resolution CO and HI to solve simultaneously for  $\alpha_{\text{CO}}$  and DGR. The solution technique finds the  $\alpha_{\text{CO}}$  that best minimizes the scatter in DGR values in  $\sim \text{kpc}$  regions across the galaxies.

We have performed a thorough investigation into the efficacy of this technique, using data from the KINGFISH key program on *Herschel*, the large IRAM 30m survey HERACLES and the THINGS HI survey with the VLA. Our tests show that above  $I_{\text{CO}} \sim 1 \text{ K km s}^{-1}$  we reliably achieve accurate solutions for  $\alpha_{\text{CO}}$ . We have used a fixed ratio between the (2–1) and (1–0) lines to present our  $\alpha_{\text{CO}}$  results on the more typically used  $^{12}\text{CO} \text{ J}=(1-0)$  scale and have shown using literature measurements that variations in the line ratio do not effect our results in these galaxies.

We find that the average  $\alpha_{\text{CO}}$  for the galaxies in our sample is  $3.1 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ . This value is slightly lower than the Milky Way  $\alpha_{\text{CO}} = 4.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ , but the MW value is well within the standard deviation of our measurements. Treating all 782 solutions independently, we find  $\alpha_{\text{CO}} = 2.6 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  with 0.4 dex standard deviation. In all averages, we have removed galaxies with inclinations higher than  $65^\circ$  since our solution pixel samples gas along the line-of-sight with a range of DGR and therefore does not conform to our main assumption—that the DGR is constant in the solution pixels.

Within the galaxies we observe a relatively flat profile of  $\alpha_{\text{CO}}$  as a function of galactocentric radius aside from in the galaxy centers. Normalizing each galaxy by its average  $\alpha_{\text{CO}}$  the average galaxy shows a factor of  $\sim 2$  lower  $\alpha_{\text{CO}}$  in its center. In several galaxies, this central value can be factors of 3 or more lower than the galaxy average. In several notable cases, the central  $\alpha_{\text{CO}}$  value is factors of 5 to 10 lower than the standard MW  $\alpha_{\text{CO}} = 4.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ .

We have investigated the correlations between  $\alpha_{\text{CO}}$  and environmental parameters in an attempt to isolate factors that drive variations in  $\alpha_{\text{CO}}$ . The strongest correlation we find is between  $\alpha_{\text{CO}}$  and stellar mass surface density ( $\Sigma_*$ ). If the strength of this correlation relative to the other parameters is real and not due to issues with measuring the other parameters, there are a number of potential explanations for why  $\alpha_{\text{CO}}$  should depend on stellar mass surface density, including the influence of ISM pressure on both molecular clouds and a more diffuse molecular medium. Distinguishing among these possibilities will require ALMA observations that resolve individual GMCs in multiple molecular gas lines across a range of extragalactic environments.

We do not observe a strong correlation between  $\alpha_{\text{CO}}$  and metallicity in our galaxies. In the range of metallicities we have sampled, this conclusion is not unexpected. The abundance of C or O does not play a major role in determining  $\alpha_{\text{CO}}$  at these metallicities since CO is optically thick in molecular clouds. The metallicity primarily influences  $\alpha_{\text{CO}}$  through the effects of dust shielding (due to the dependence of DGR on metallicity). Models and simulations have suggested that dust shielding can influence the amount of gas in “CO-dark” layers of GMCs, but at MW metallicity, only  $\sim 30\%$  of the gas is in this layer. At lower metallicities, a strong dependence of  $\alpha_{\text{CO}}$  on metallicity has been observed using the same technique we employ (Leroy et al. 2011).

In the centers of several galaxies, we find  $\alpha_{\text{CO}}$  values 5–10 times lower than the MW  $\alpha_{\text{CO}}$ . These regions are also significantly below the average  $\alpha_{\text{CO}}$  for their galaxy.



Comparison of our measured  $\alpha_{\text{CO}}$  with values from the literature shows good agreement between our dust-based results and multi-line modeling results. In contrast, our  $\alpha_{\text{CO}}$  values in these regions can be much lower than  $\alpha_{\text{CO}}$  determined from virial mass based techniques. The discrepancy with virial mass measurements becomes smaller at larger galactocentric radii, suggesting this is a particular property of the gas in galaxy centers. At the resolution of our observations, the central region with low  $\alpha_{\text{CO}}$  is unresolved ( $\lesssim$  kpc). We suggest several potential explanations for the low  $\alpha_{\text{CO}}$  value and the fact that it is not reflected in virial masses including ISM pressure contributions to GMC virial balance, increases in molecular gas temperature and/or a more diffuse molecular medium similar to what is found in ULIRGs. With the limited amount of  $^{13}\text{CO}$  and other molecular line observations in this region, it is not possible to distinguish between these scenarios, but NGC 6946 at least shows some evidence for potentially lower CO optical depth towards its center. As is explored in Leroy et al. (submitted), these galaxy centers show enhanced star-formation efficiencies when we apply our  $\alpha_{\text{CO}}$ , close to what is seen along the “starburst sequence” in ultra-luminous infrared galaxies (e.g. Daddi et al. 2010).

In addition to  $\alpha_{\text{CO}}$  we also simultaneously measure DGR in all of our regions. On average, we find  $\text{Log}(\text{DGR}) = -1.86$  treating all solution pixels equally, with a standard deviation of 0.22 dex. When we force each galaxy to contribute equally, the average is essentially indistinguishable from the MW DGR. Unlike  $\alpha_{\text{CO}}$ , DGR is well-correlated with metallicity, with a slope slightly shallower than linear (although this slope is mainly due to NGC 3184 being offset from the main trend, removing it from the sample gives a slope consistent with linear). The approximately linear dependence of DGR on metallicity agrees with the predictions of dust evolution models, but our measurements do not cover a wide enough metallicity range to distinguish between them.

The results presented here suggest a picture where  $\alpha_{\text{CO}}$  is slightly lower than the typical value of  $4.4 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  in the disks of most galaxies, and mainly constant as a function of radius despite changes in metallicity, radiation field intensity and star-formation rate surface density. Galaxy centers appear to be a different regime, where external pressure or changes in the character of molecular gas (i.e. mostly confined to self-gravitating GMCs versus a more diffuse molecular medium) may bring about large changes in  $\alpha_{\text{CO}}$ . Through the galaxy, however, DGR appears to be an approximately linear function of metallicity. The simple behavior of DGR provides a unique tool to study the ISM in nearby galaxies, if we can obtain measurements of metallicity gradients with trustworthy calibration.

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## APPENDIX

TECHNIQUE FOR SIMULTANEOUSLY DETERMINING DGR AND  $\alpha_{\text{CO}}$ 

Prior to choosing the technique described in Section 3 we have explored a variety of possible ways to simultaneously constrain DGR and  $\alpha_{\text{CO}}$ . The various techniques represent, in essence, different ways to judge how uniform the DGR is in the region in question, at any given value of  $\alpha_{\text{CO}}$ . After defining these variations on the essential technique, we construct simulated datasets with known  $\alpha_{\text{CO}}$  and DGR and realistic statistical errors and intrinsic scatter to test the solution techniques. These simulated data tests allow us to optimize the performance of the technique given the properties of our dataset.

*Potential Techniques*

The general procedure for finding the most “uniform” DGR in the solution pixel given the spatially resolved measurements of  $\Sigma_{\text{HI}}$ ,  $\Sigma_{\text{D}}$ , and  $\text{I}_{\text{CO}}$  is to step through a grid of  $\alpha_{\text{CO}}$  values, calculate DGR at each sampling point in the solution pixel using that  $\alpha_{\text{CO}}$ , measure some statistic that can be used to judge how uniform the DGR values are across the region and finally, either minimize or maximize that statistic as a function of  $\alpha_{\text{CO}}$ . Below we describe the various statistics we have tested to judge the uniformity of the DGR values in a given region. The reason we investigate all of these possible statistics is because each weights outliers differently, and it is not obvious *a priori* which will work best to recover the underlying  $\alpha_{\text{CO}}$ . For techniques that involve minimizing scatter in the DGR, we use three different statistics to measure scatter: the standard deviation (RMS), the median absolute deviation (MAD) and a robust estimator of the standard deviation from Tukey’s biweight (BIW) (Press et al. 2002).

1. Minimum Fractional Scatter in DGR (FS): At each value of  $\alpha_{\text{CO}}$  we calculate the DGR for all points in the region in question. We then divide each DGR value by the mean DGR in the region and measure the scatter of the resulting values (with RMS, MAD and BIW statistics).
2. Minimum Logarithmic Scatter in DGR (LS): At each  $\alpha_{\text{CO}}$  we calculate the scatter of the logarithm of the DGR values (with RMS, MAD and BIW). This is similar to the minimization of fractional scatter, but with a different weighting for the individual points. This also throws away data points with negative values, since their logarithm is undefined.
3. Maximum Correlation Coefficient of  $\Sigma_{\text{D}}$  and  $\Sigma_{\text{Gas}}$  (LC or RC): At each value of  $\alpha_{\text{CO}}$  we compute the linear and rank correlation coefficients between  $\Sigma_{\text{D}}$  and  $\Sigma_{\text{gas}} = \Sigma_{\text{HI}} + \alpha_{\text{CO}}\text{I}_{\text{CO}}$ . The best  $\alpha_{\text{CO}}$  value will maximize the correlation between these two quantities.
4. Minimum  $\chi^2$  of Best-Fit Plane to  $\text{I}_{\text{CO}}$ ,  $\text{N}_{\text{HI}}$  and  $\Sigma_{\text{D}}$  (PF): The  $\Sigma_{\text{D}}$ ,  $\Sigma_{\text{HI}}$  and  $\Sigma_{\text{H}_2}$  values describe a plane with two free parameters. At each value of  $\alpha_{\text{CO}}$  we fit a plane to the measurements to determine DGR. The best value of  $\alpha_{\text{CO}}$  will be the one that minimizes the  $\chi^2$  of the best-fit plane.
5. Minimum Correlation Coefficient of DGR vs.  $\text{I}_{\text{CO}}/\text{N}_{\text{HI}}$  (CHC): In this technique we search for the  $\alpha_{\text{CO}}$  value that minimizes the correlation of DGR with  $\text{I}_{\text{CO}}/\text{N}_{\text{HI}}$ . This technique weights the points differently depending on how much local  $\Sigma_{\text{gas}}$  depends on  $\alpha_{\text{CO}}$ .

*Definition of the “Solution Pixel” Size and Location*

A key aspect of the technique we use to constrain DGR and  $\alpha_{\text{CO}}$  is defining the region over which we assume there to be one value each of DGR. Under ideal circumstances, the regions would be as small as possible given the resolution of the maps. Realistically, however, there are several considerations that must be taken into account when defining the regions including: covering an adequate range of CO/HI ratios, having enough points to measure scatter accurately, and keeping the region to  $\sim\text{kpc}$  scales over which it is reasonable to assume that the DGR is indeed constant..

To complement the hexagonal, half-beam spaced grid with which we sampled the original data (i.e. our “sampling points”) we again use hexagonal spacings to define the “solution pixels” as the individual samples can be divided naturally into concentric hexagons. We tested a variety of solution pixel sizes ranging from 19-point to 271-point hexagons.

We found that we 37-point solution pixels was a good compromise between size and solution quality. Because of the underlying half-beam spaced sampling grid, the 37 point solution pixel contains  $\sim 9$  independent measurements. For the next smallest possible hexagon (19-points), there are not sufficient numbers of independent measurements to reliably judge the scatter in the DGR.

In order to fully sample the map, the center of each hexagonal pixel is offset by  $1/2$  of the spacing from its neighbor. This results in the “solution pixels” not being independent—each neighboring pixel shares  $\sim 40\%$  of the same data (the oversampling can be exactly described as  $n^2/(3n^2 - 3n + 1)$  for concentric hexagons).

### *Test of the Solution Technique with Simulated Data*

We have investigated the efficacy of the various techniques using simulated data modeled on our observations. Our goal is to identify the technique or techniques that return the most accurate values of  $\alpha_{\text{CO}}$  and DGR over the range of conditions and signal-to-noise levels in our dataset. We also aim to characterize any biases in the recovered  $\alpha_{\text{CO}}$  as a function of input  $\alpha_{\text{CO}}$  and S/N. In performing these tests, it is important to model the simulated data on our real observations. This is because the ability of the techniques to judge the DGR uniformity depend not only on the S/N of the measurements but also on the range of CO/HI ratios. Since CO and HI can be correlated, anti-correlated or independent of each other on kiloparsec scales, depending on the state of the ISM, it is difficult to generate a reasonable set of simulated data from scratch that encompasses the range of CO/HI behaviors in the observations. Therefore, we expect the best test of the technique will come from simulated data that are closely modeled on the observations. In the following, we describe how the simulated data are generated and discuss the results of the test.

The simulated data are generated via a Monte Carlo procedure in which we randomly choose a galaxy from our sample (listed in Table 1) at SPIRE 350 resolution, choose a solution pixel and create simulated data based on the selected CO, HI and  $\Sigma_{\text{D}}$  samples. For each trial we randomly sample a range of  $\alpha_{\text{CO}}$  values between  $0.5 - 50 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  and intrinsic scatter per axis (evenly divided among the  $\text{I}_{\text{CO}}$ ,  $\Sigma_{\text{HI}}$  and  $\Sigma_{\text{D}}$  axes, for lack of better knowledge of the sources of intrinsic scatter) between  $0.0 - 0.4$  dex. We note that because of the properties of lognormal distributions, the scatter in the DGR is not simply  $\sqrt{3} \times$  the input intrinsic scatter per axis, so we approximate it after-the-fact using the input scatter per axis and the mean  $\text{H}_2/\text{HI}$  ratio for the simulated measurements.

Our procedure is the following: 1) select the observations with the sampling described above, 2) use the  $\text{I}_{\text{CO}}$  and  $\Sigma_{\text{HI}}$  measurements along with the random  $\alpha_{\text{CO}}$  value to create a simulated  $\Sigma_{\text{gas}}$  vector, 3) calculate the DGR value that preserves the average S/N level of the  $\Sigma_{\text{D}}$  measurements and create a simulated, noise-free  $\Sigma_{\text{D}}$  vector by multiplying the  $\Sigma_{\text{gas}}$  from step 2 by this DGR, 4) apply the randomly-selected intrinsic scatter to each axis and 5) add simulated measurement errors according to the observed uncertainties in the  $\text{I}_{\text{CO}}$ ,  $\Sigma_{\text{HI}}$  and  $\Sigma_{\text{D}}$  maps. These simulated measurements are then used as input to solve for  $\alpha_{\text{CO}}$  and DGR using the techniques described above.

From this Monte Carlo simulation, we can then choose the technique that is the most robust (i.e. most frequently achieves a solution) and accurate (i.e. to get closest to the known input  $\alpha_{\text{CO}}$ ). In Figure 17 we show the results of this simulation for the techniques we have outlined. The panels show (left) the mean difference between the input and recovered  $\alpha_{\text{CO}}$  value, (middle) the standard deviation of the difference of the input and recovered  $\alpha_{\text{CO}}$ , and (right) the percent of the Monte Carlo trials that achieve a solution. These values are binned in a two-dimensional space defined by the intrinsic scatter added to the simulated data and the median S/N of the simulated CO measurements.

It is clear that the FS and LS techniques provide the least bias in the recovered  $\alpha_{\text{CO}}$  over the relevant range of intrinsic scatter and S/N (except for the FS\_RMS which is significantly biased at low CO S/N). The correlation coefficient (LC and RC), plane fit (PF) and CO/HI correlation (CHC) techniques all provide much more limited regions with low bias in the recovered  $\alpha_{\text{CO}}$  as well as having a lower fraction of solutions. In general the MAD based techniques have slightly less bias towards the low CO S/N region, but show a larger scatter between the input and recovered  $\alpha_{\text{CO}}$ . Overall, we find that the LS\_BIW (robust biweight mean of the logarithmic scatter) is the technique that shows the best performance in accuracy, precision and robustness over the range of characteristics of our dataset.

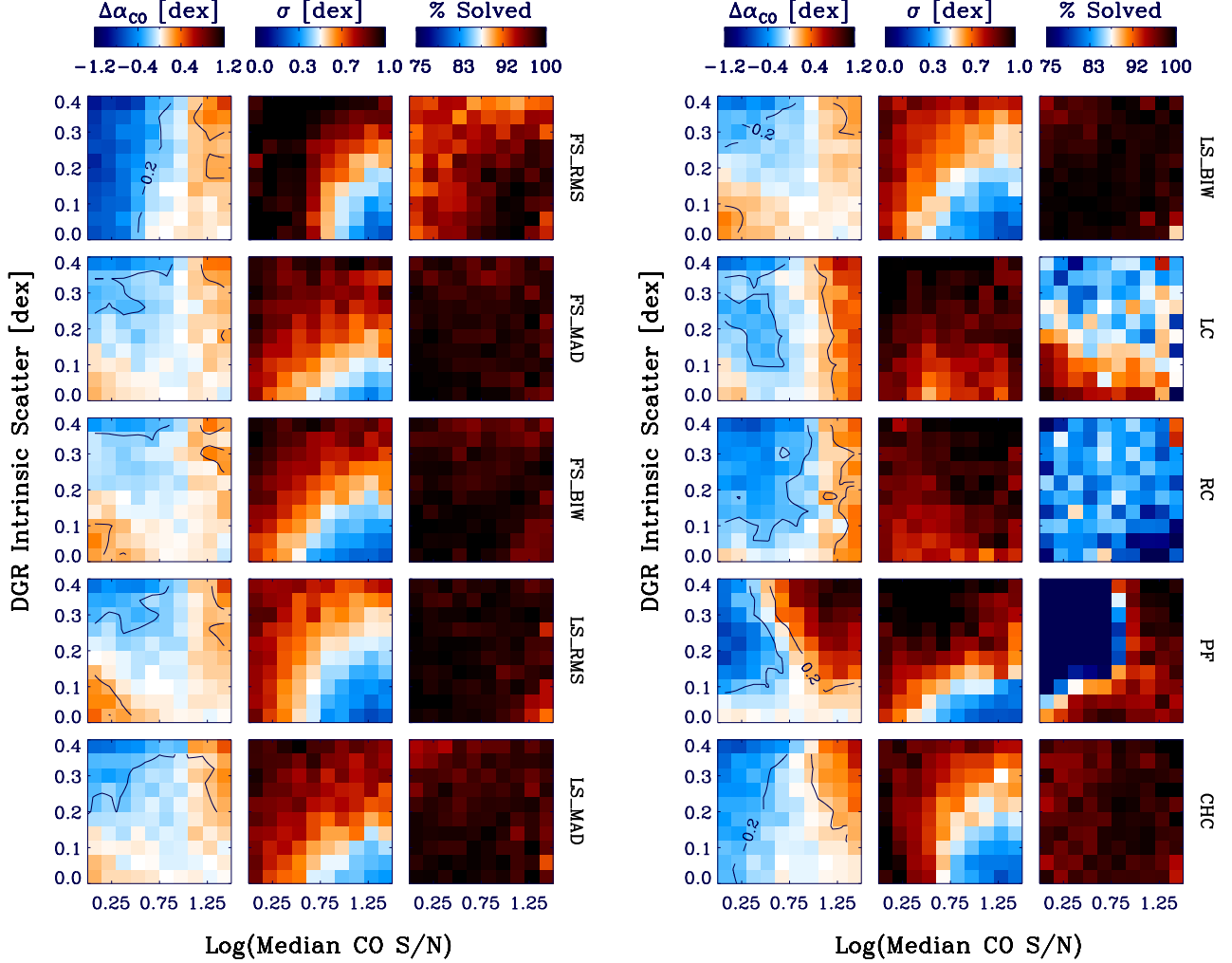
In addition to helping us choose the best technique, the tests with simulated data also allow us to investigate how the measured minimum in the logarithmic scatter corresponds to the known intrinsic scatter added to the simulated data. In addition to being an interesting quantity scientifically, the measured scatter can also help us to identify which region of the parameter space a given solution falls in, allowing us to judge how biased we expect it to be given our knowledge from these simulated data tests. Figure 18 shows a comparison of the known input intrinsic scatter with the measured minimum in the logarithmic scatter for the LS\_BIW technique. Most of the outliers come from regions with low CO S/N. At very low levels of intrinsic scatter, the measured scatter is larger due to the influence of observational uncertainties. In general, however, the measured minimum log scatter is a very good proxy for the intrinsic scatter in the DGR.

Based on these results with simulated data, we can use the measured median CO S/N and the measured minimum of the scatter in the DGR values to predict how biased and how uncertain a given determination of  $\alpha_{\text{CO}}$  for our dataset. To do this we use the measured minimum in the DGR scatter as an estimate of the intrinsic DGR scatter (it is biased slightly higher, but this is a minor effect and represents a conservative estimate of the intrinsic scatter). Then using this value and the median CO S/N in the solution pixel we interpolate in the grid presented in Figure 17 for “LS\_BIW” to predict the bias inherent in the technique.

### *Testing for Potential Bias at High CO S/N and Low $\Sigma_{\text{HI}}$*

One of the key results of our work is the measurement of low  $\alpha_{\text{CO}}$  values in the centers of some galaxies (see Section 6.3). These locations are outliers from the average solution pixel in the sense of having high CO S/N and often a relative deficiency in  $\Sigma_{\text{HI}}$ . Since they make up a small subset of all solution pixels, our Monte Carlo simulation from the previous Section may not adequately judge the bias of the technique in these regions, since they are not sampled frequently enough (only 26 out of  $\sim 900$  solution pixels). We therefore perform a separate Monte Carlo simulation for the galaxy centers in order to verify that these low  $\alpha_{\text{CO}}$  values are not due to biases in the technique (we have demonstrated that the average pixel in the sample is not biased using the experiment in the previous section).

The results of the technique are biased if it returns an  $\alpha_{\text{CO}}$  systematically different from the true  $\alpha_{\text{CO}}$ . For this test, we will define several different  $\alpha_{\text{CO}}$  values. First,  $\alpha_{\text{CO, meas}}$  is the measured value for a given solution pixel, we



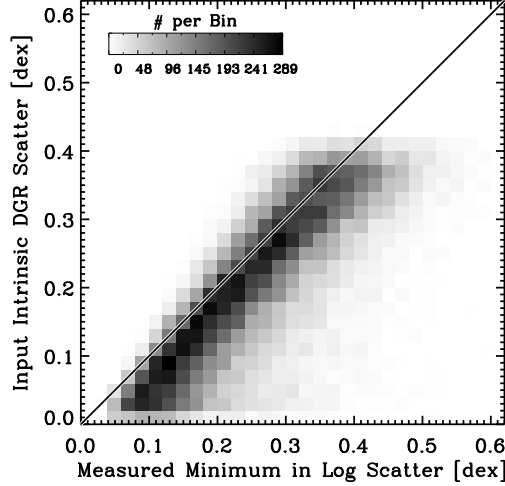
**Figure 17.** Results of simulated data tests to optimize the solution technique. Columns correspond to: left, the difference between the known input  $\alpha_{\text{CO}}$  and the recovered best-solution  $\alpha_{\text{CO}}$  ( $\Delta\alpha_{\text{CO}}$ ); middle, the standard deviation of the difference between input and recovered  $\alpha_{\text{CO}}$  ( $\sigma$ ); and right, the fraction of trials in each bin where a solution is achieved. The results are presented as two-dimensional histograms, binned in CO S/N and the simulated intrinsic scatter added to the data. The rows show results for the various solution techniques described previously. From top to bottom in the left panel these are: minimization of the fractional scatter using the mean (FS\_RMS), median (FS\_MAD) and robust mean (FS\_BIW) and the minimization of the logarithmic scatter using the mean (LS\_RMS) and median (LS\_MAD). In the right panel we show minimization of the logarithmic scatter using the robust mean (LS\_BIW), minimizing the linear correlation coefficient (LC), minimizing the rank correlation coefficient (RC), minimizing the  $\chi^2$  of the best-fit plane (PF) and minimizing the correlation coefficient between DGR and  $\text{I}_{\text{CO}}/\Sigma_{\text{HI}}$  (CHC). The contours in the  $\Delta\alpha_{\text{CO}}$  column show the regions of parameter space where the difference in the input and recovered  $\alpha_{\text{CO}}$  is less than 0.2 dex. The LS\_BIW technique minimizes the difference between input and recovered  $\alpha_{\text{CO}}$  and achieves a small  $\sigma$  over the largest area, although the distinction from FS\_BIW is not large.

do not know if this measured value is biased, it is only what we have measured for that pixel given the true data. Second,  $\alpha_{\text{CO},\text{in}}$  is a known  $\alpha_{\text{CO}}$  value we have used to generate simulated data. Finally,  $\alpha_{\text{CO},\text{out}}$  is the  $\alpha_{\text{CO}}$  value that we recover for  $\alpha_{\text{CO},\text{in}}$  using our solution technique.

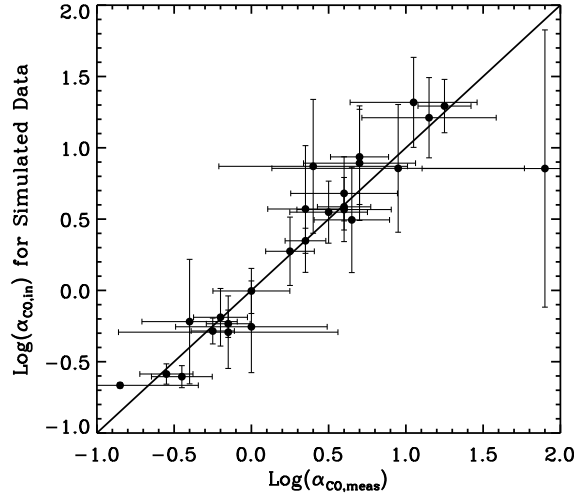
The essence of this test is that we take a range of  $\alpha_{\text{CO},\text{in}}$  values and map them to their  $\alpha_{\text{CO},\text{out}}$  values, by generating simulated data given  $\alpha_{\text{CO},\text{in}}$  and running it through our solution technique. This simulated data generation proceeds as described in the previous section and is designed to preserve the CO/HI ratio and S/N of the measurements for a given pixel. In addition to observational noise, we also add intrinsic scatter between 0.01–0.1 dex to the simulated data, which reflects the level of intrinsic scatter we have found in the real solutions. For each solution pixel we generate  $10^4$  random  $\alpha_{\text{CO},\text{in}}$  values that span our range of  $\alpha_{\text{CO}} = 0.1 - 100$ .

With this simulation, we can determine for any given value of  $\alpha_{\text{CO},\text{out}}$ , which values of  $\alpha_{\text{CO},\text{in}}$  ended up there. If a solution is biased, the correspondence between  $\alpha_{\text{CO},\text{in}}$  and  $\alpha_{\text{CO},\text{out}}$  will not be one-to-one. For example, a bias may make us consistently recover  $\alpha_{\text{CO},\text{out}} = 1 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$  when  $\alpha_{\text{CO},\text{in}} = 0.1 \text{ M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ .

In judging the biases of the actual solutions for our central solution pixels, we then select all of the  $\alpha_{\text{CO},\text{out}}$  measurements equal to  $\alpha_{\text{CO},\text{meas}}$  and find the mean and standard deviation of the  $\alpha_{\text{CO},\text{in}}$  values that gave those results. In Figure 19 we show a plot of the mean and standard deviation of the  $\alpha_{\text{CO},\text{in}}$  values versus the  $\alpha_{\text{CO},\text{meas}}$  plus its uncertainty for all galaxy centers in the sample. This figure shows that within the uncertainties of  $\alpha_{\text{CO},\text{meas}}$ , none of the central pixel measurements show a bias.



**Figure 18.** Results of simulated data tests comparing the known input intrinsic scatter in DGR with the recovered minimum in the DGR scatter. The gray scale represents the number of trials falling in a given bin. We have uniformly sampled input intrinsic scatter values between 0.0 – 0.4 dex. The red line shows a one-to-one relationship.

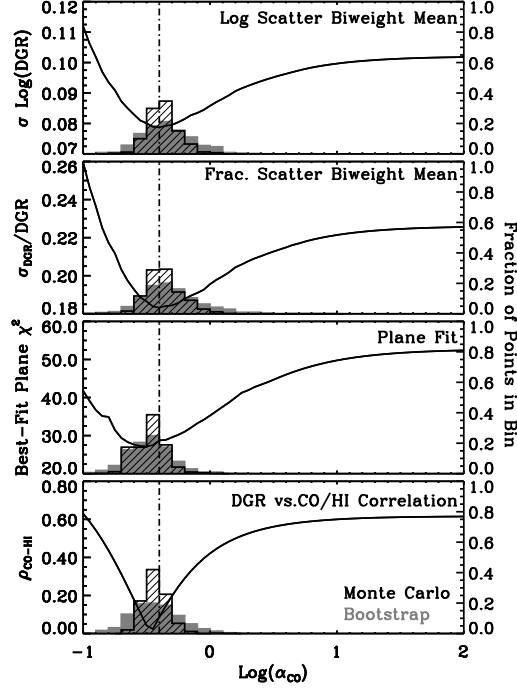


**Figure 19.** This figure shows the results of simulated data tests focused on the galaxy centers, where high CO S/N and high CO/HI ratios could potentially bias the recovered  $\alpha_{\text{CO}}$ . The  $x$ -axis shows the measured  $\alpha_{\text{CO, meas}}$  and uncertainty for each of the 26 central points in our sample. The  $y$ -axis shows the mean and standard deviation of the *known*, *input*  $\alpha_{\text{CO, in}}$  values from the simulations where we recovered  $\alpha_{\text{CO, out}}$  equal to the value we have measured. This test shows that the  $\alpha_{\text{CO}}$  values we measured in the galaxy centers are not biased within their uncertainties.

In addition, a second check on these low central  $\alpha_{\text{CO}}$ , at least for NGC 6946, is shown in Figure 20 where we show the minimization curve for several techniques towards its central solution pixel. All techniques agree within their errors, highlighting the minimum at  $\alpha_{\text{CO}} \sim -0.4$ . This emphasizes that the low  $\alpha_{\text{CO}}$  found in the center is not an artifact of the particular technique we are using, but can be recovered via minimization of scatter in the DGR, minimization of the correlation coefficient between CO/HI and DGR and minimization of the  $\chi^2$  of the best-fit plane to CO, HI and  $\Sigma_{\text{D}}$ .

#### *Summary of Investigations into the Solution Technique*

To summarize, we have tested a number of variations on the basic technique of finding the most “uniform” DGR in a given region by stepping through a grid of  $\alpha_{\text{CO}}$  values. We created simulated data with known  $\alpha_{\text{CO}}$  and DGR intrinsic scatter matched to the range of S/N in our dataset. Via a Monte Carlo simulation, we found the robust mean of the logarithmic scatter to be the technique that spans the range of CO S/N and possible intrinsic DGR scatter with the highest accuracy and rate of success. Given knowledge of the CO S/N for a region and the measured minimum of the logarithmic scatter, we can use the simulated data tests to constrain how biased our  $\alpha_{\text{CO}}$  measurement can be. We have also specifically checked that the central regions of galaxies, which only comprise 26 pixels out of the sample, are not biased due to their sometimes unusual CO/HI ratios. We found no significant bias for these solutions and show in addition that a variety of techniques can reproduce the low central  $\alpha_{\text{CO}}$  solutions, not just the minimization of the

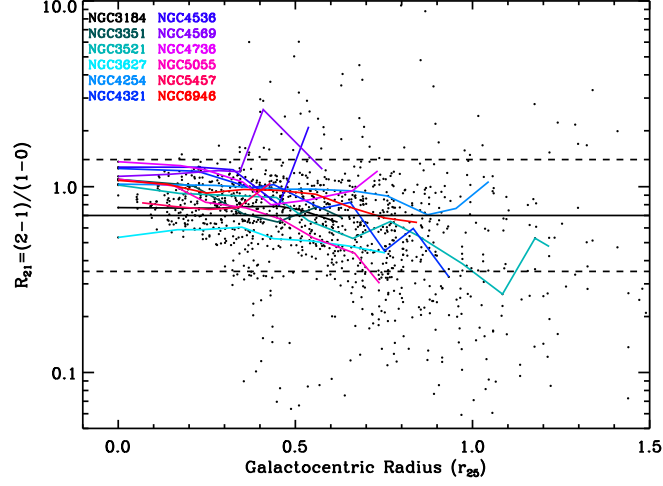


**Figure 20.** Solution for the central region of NGC 6946. The panels show different statistics we use to measure the uniformity of the DGR in a given solution pixel, all showing a clear minimum at  $\alpha_{\text{CO}} = 0.4 M_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$ . A thorough discussion of the various statistics is presented in the Image Atlas. From top to bottom we show: the scatter in  $\text{Log}(\text{DGR})$  measured using the robust biweight mean (LS-BIW); the fractional scatter DGR determined with the biweight mean (FS-BIW); the  $\chi^2$  of the best-fit plane to  $I_{\text{CO}}$ ,  $\Sigma_{\text{HI}}$  and  $\Sigma_{\text{D}}$  (PF); and the correlation coefficient between DGR and the CO/HI ratio (CHC). The dot-dash vertical line shows the solution for  $\alpha_{\text{CO}}$  from the LS-BIW technique, which is what we adopt in the rest of the study. The agreement between different techniques (i.e. minimizing scatter in DGR, plane-fit and minimizing the correlation between DGR and CO/HI) illustrates the high confidence of this solution and shows that it is not an artifact of the solution technique.

DGR scatter.

#### Variations in $R_{21}$

In Figure 21 we show the measured CO  $(2-1)/(1-0)$  line ratio in the solution pixels we have defined for each galaxy (the black points) and in radial profiles (colored lines). The assumed  $R_{21}$  is shown with a horizontal solid, black line and a factor of 2 above and below that value are marked with black dashed lines. There are variations in  $R_{21}$ , but in regions with good CO S/N (the only regions in which we will achieve good solutions) these are generally less than a factor of two away from the  $R_{21}$  we have assumed. This deviation is within the uncertainties on the  $\alpha_{\text{CO}}$  solutions, which typically have 0.2 dex uncertainty, at minimum.



**Figure 21.** The ratio of the CO  $J=(2-1)$  and  $(1-0)$  intensities measured from HERACLES and Nobeyama observations, respectively. The black points show all of the individual measurements from the solution pixels and the colored lines show radial profiles, binned by  $0.1r_{25}$ . The value we have assumed for converting our  $(2-1)$   $\alpha_{\text{CO}}$  measurements to the more commonly used  $(1-0)$  scale is shown with a solid black line ( $R_{21} = 0.7$ ), and the dashed lines show factors of 2 above and below that value. The variations of  $R_{21}$  are generally less than a factor of 2, which is less than the uncertainty on most of our  $\alpha_{\text{CO}}$  measurements. Note that variations in  $R_{21}$  only affect the  $(1-0)$   $\alpha_{\text{CO}}$ , since we are directly measuring the conversion factor appropriate for the  $(2-1)$  line.



## APPENDIX

## ATLAS OF GALAXIES AND RESULTS

In the following Appendix we present the results for individual solution pixels in all of the galaxies we have considered. In the top panel of Figures 22 through Figure 46 we show the HI, CO and  $\Sigma_{\text{D}}$  maps at matched resolution. The circles overlaid on these figures show the central position of each of the 37-point, hexagonal solution pixels in which we determine  $\alpha_{\text{CO}}$ . In the middle panel of these same figures we show the  $\alpha_{\text{CO}}$  values on the left in color and the associated uncertainties in the right in gray scale. Finally, in the bottom panels of the figures, we plot the measured  $\alpha_{\text{CO}}$  values as a function of galactocentric radius ( $r_{25}$ ). The color of the points in this plot reflects the uncertainties on the  $\alpha_{\text{CO}}$  values as shown in the gray scale color table in the middle panel.

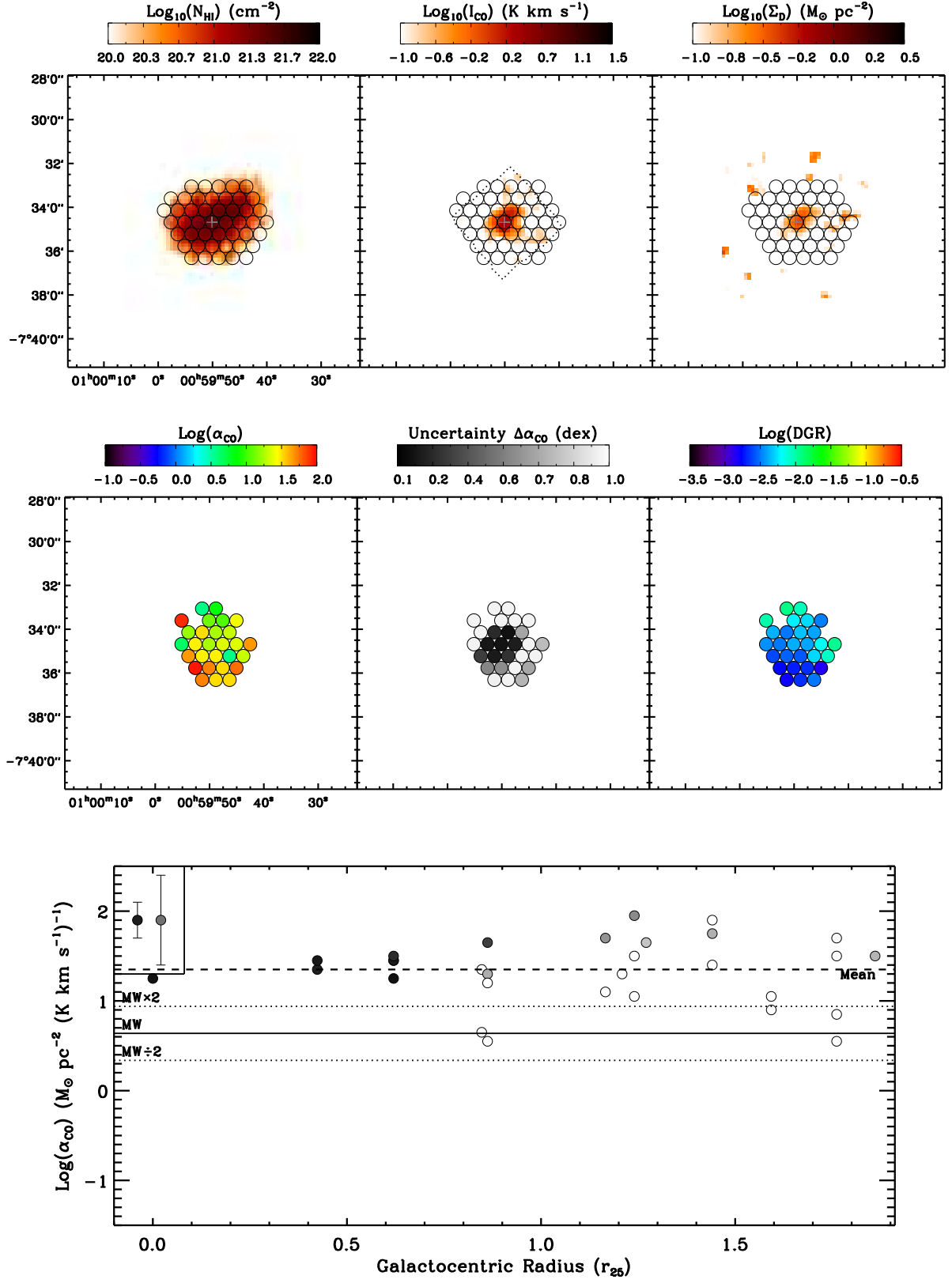


Figure 22. Results for NGC 0337.

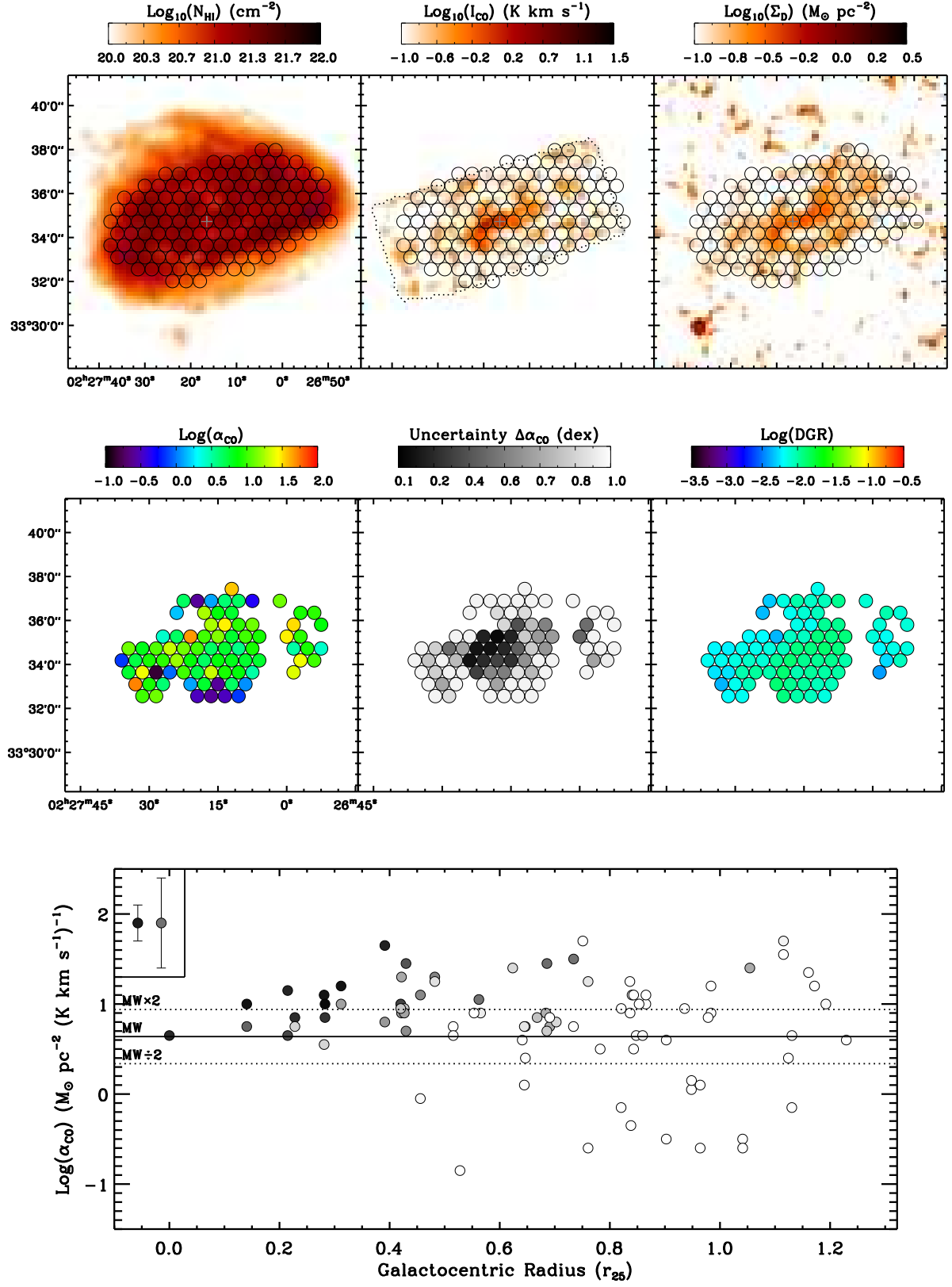


Figure 23. Results for NGC 0925.

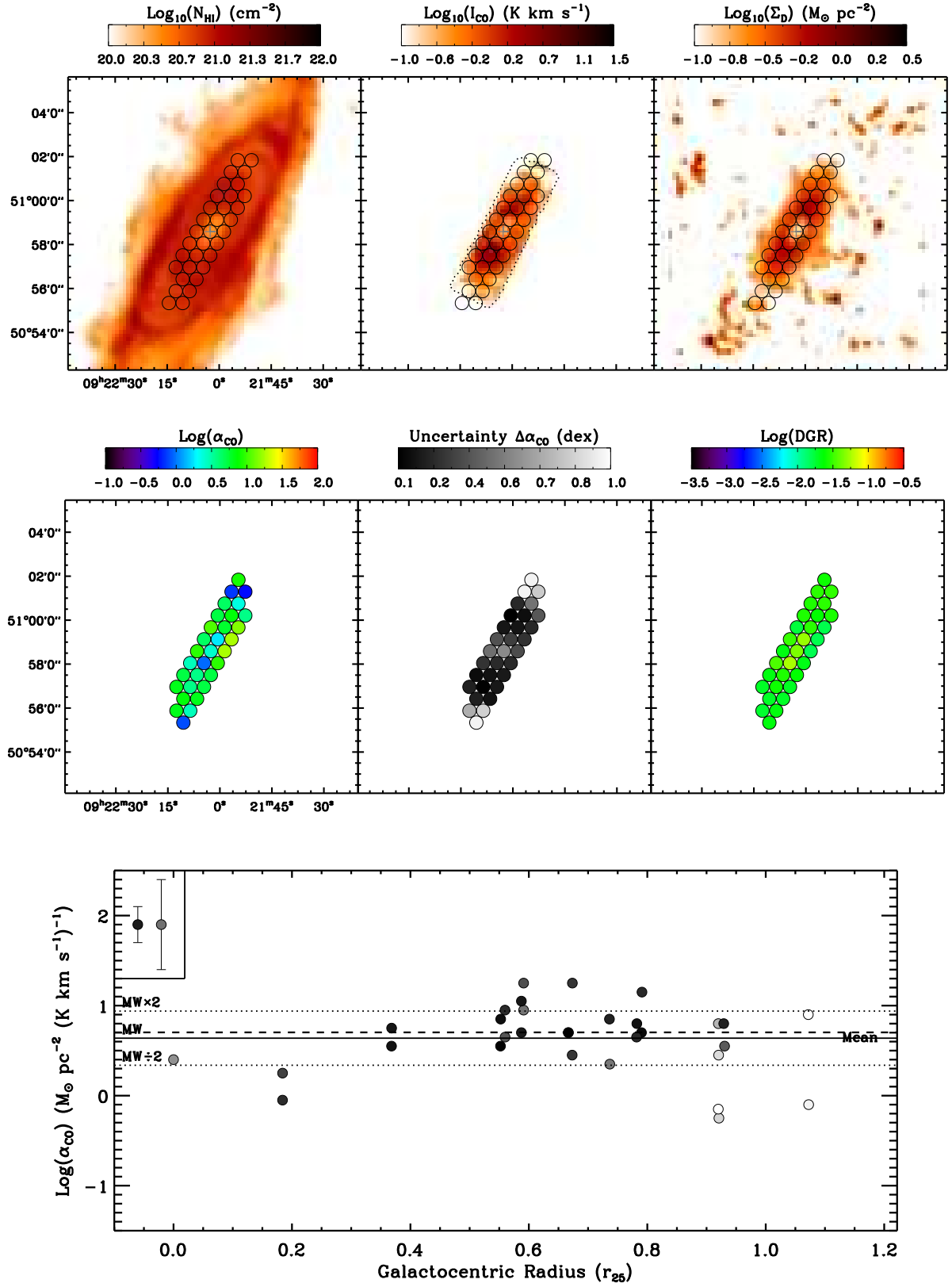


Figure 24. Results for NGC 2841.

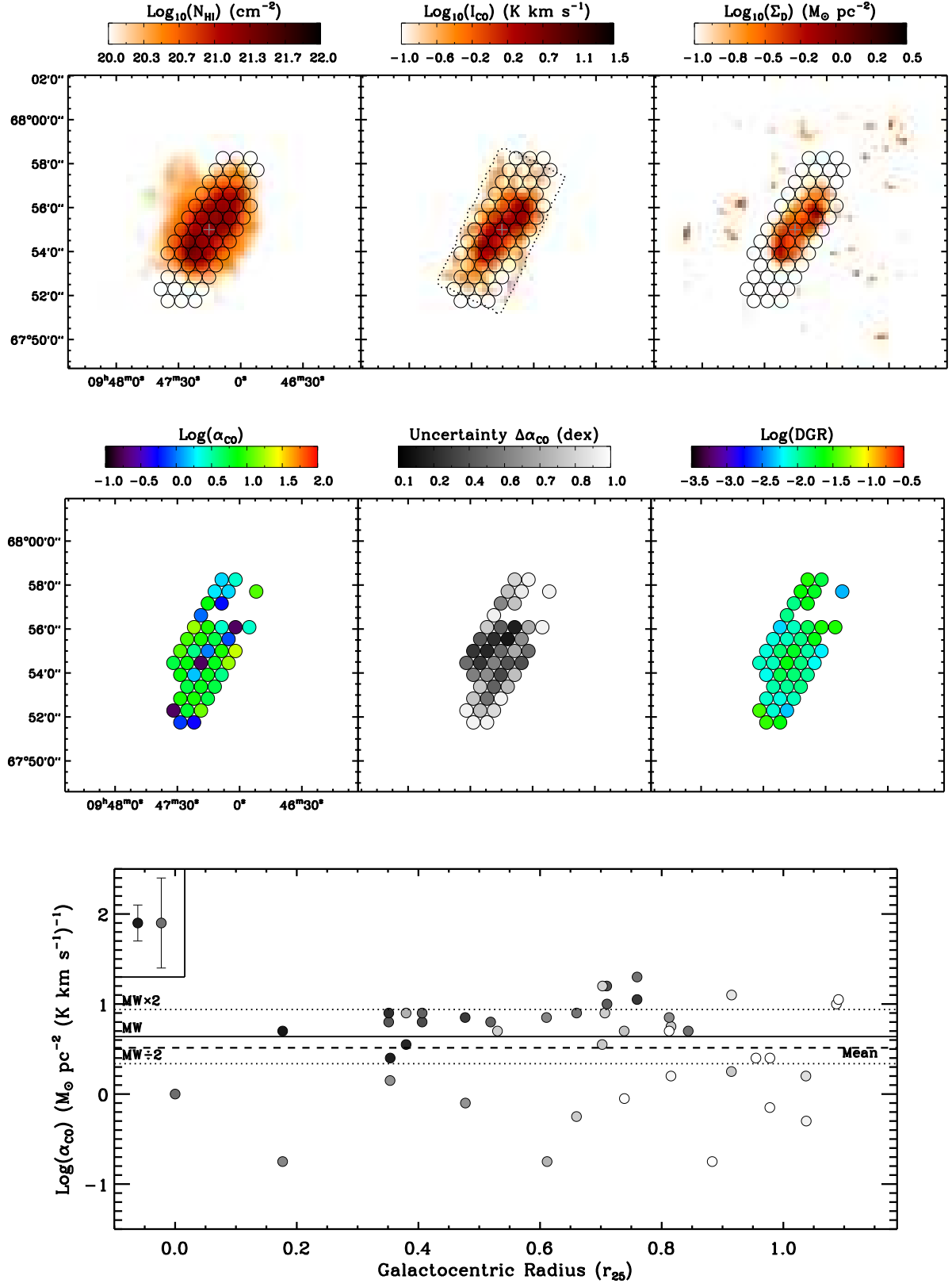


Figure 25. Results for NGC 2976.

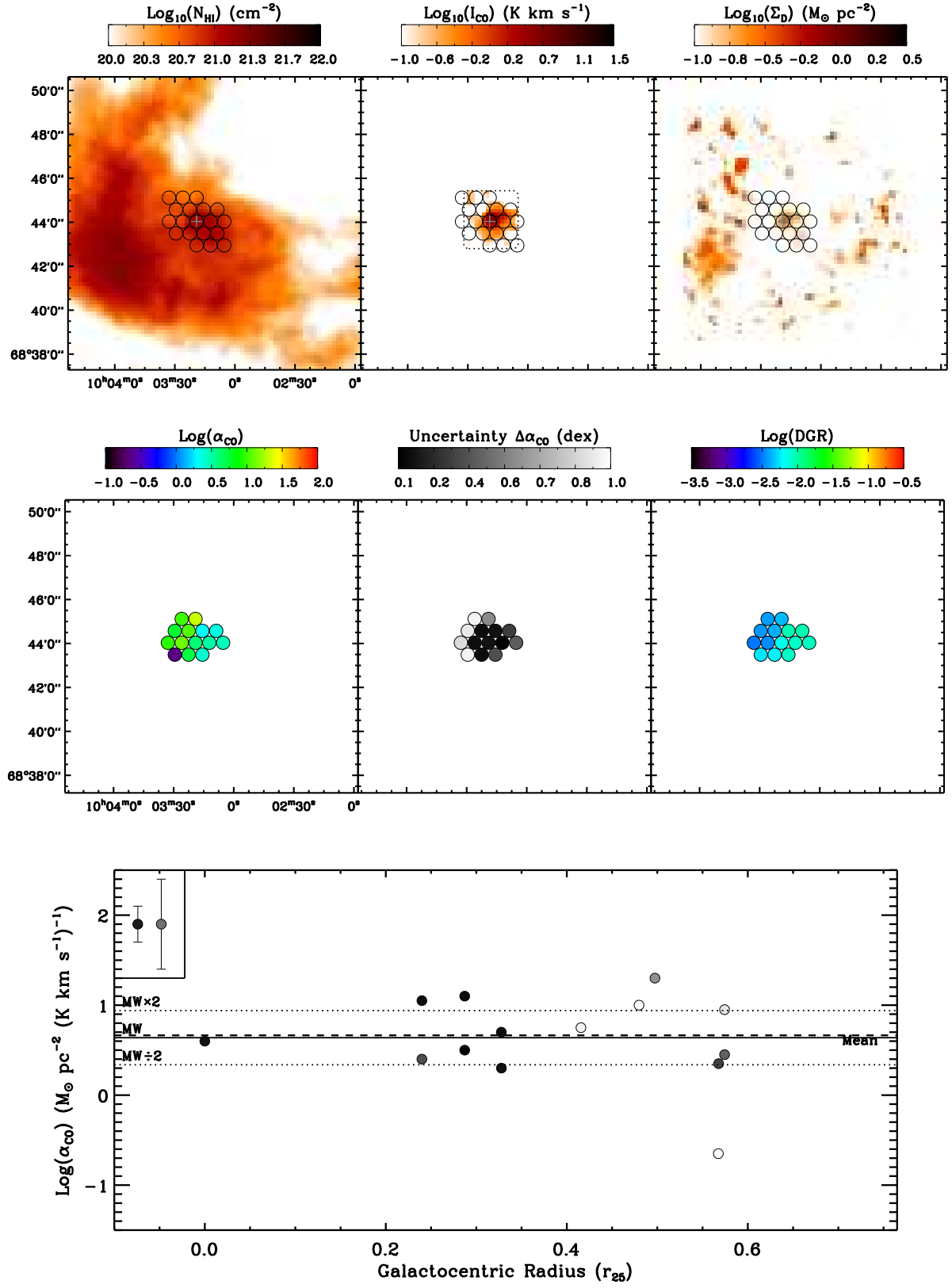


Figure 26. Results for NGC 3077.

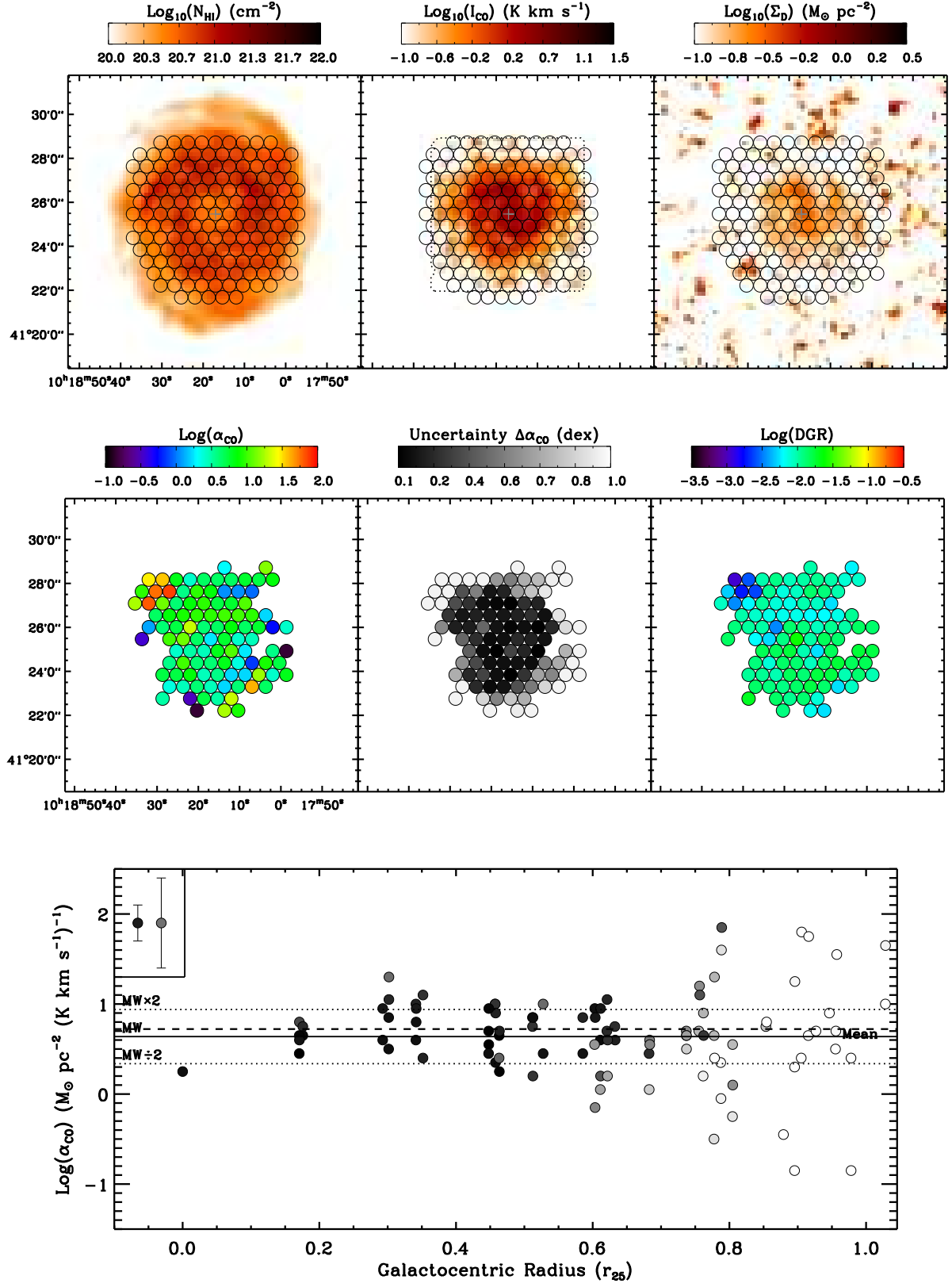


Figure 27. Results for NGC 3184.

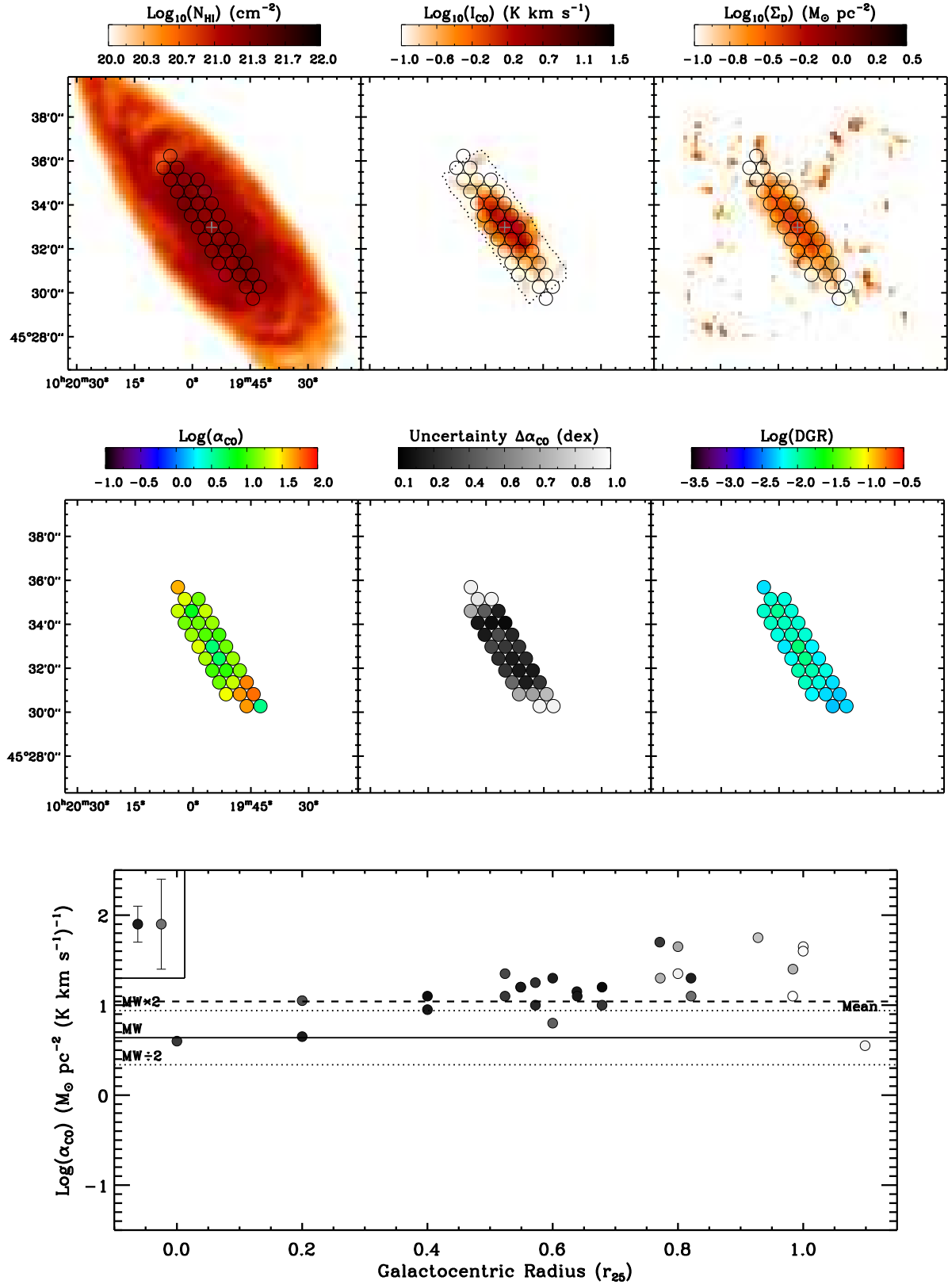


Figure 28. Results for NGC 3198.



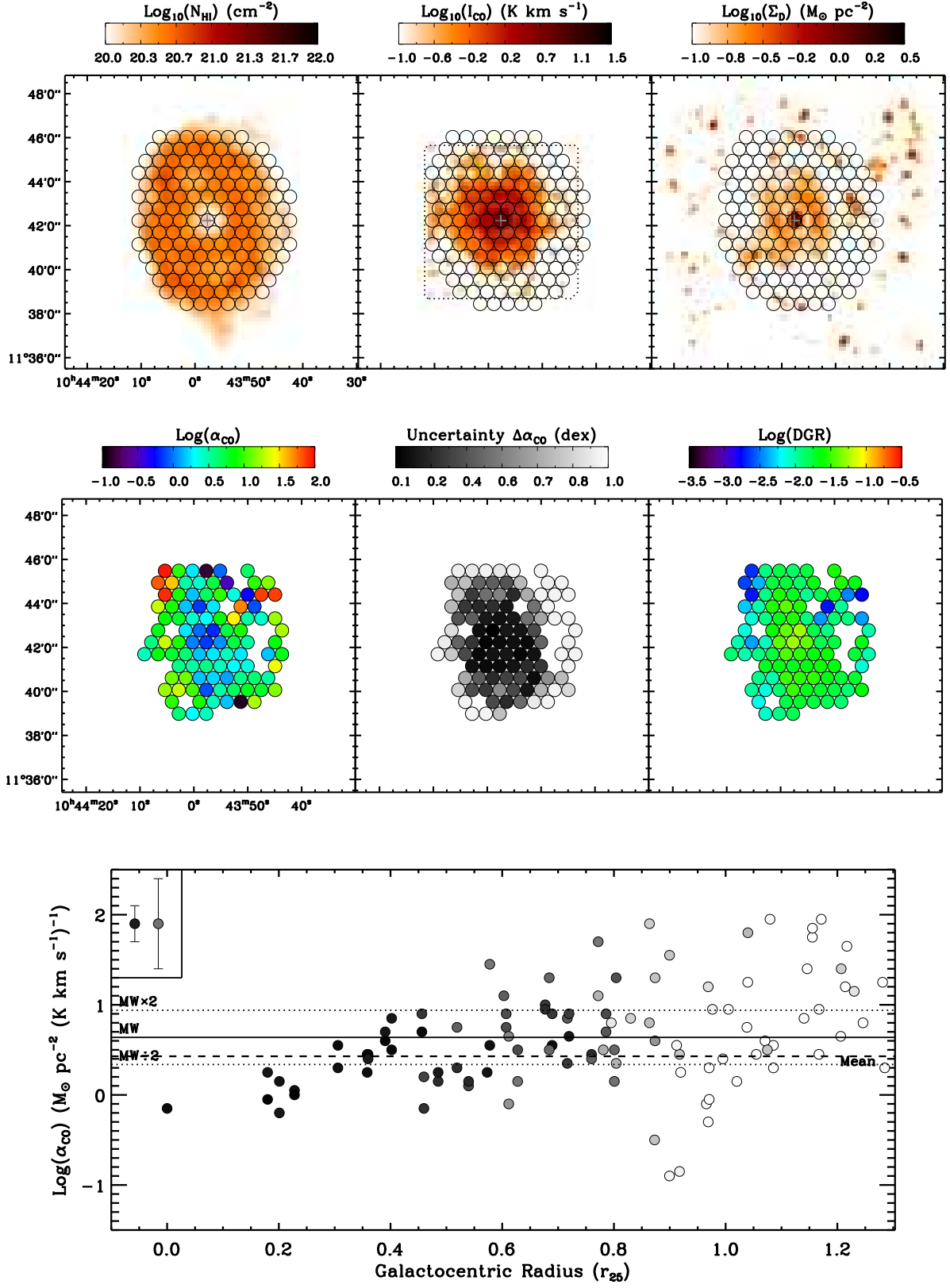


Figure 29. Results for NGC 3351.

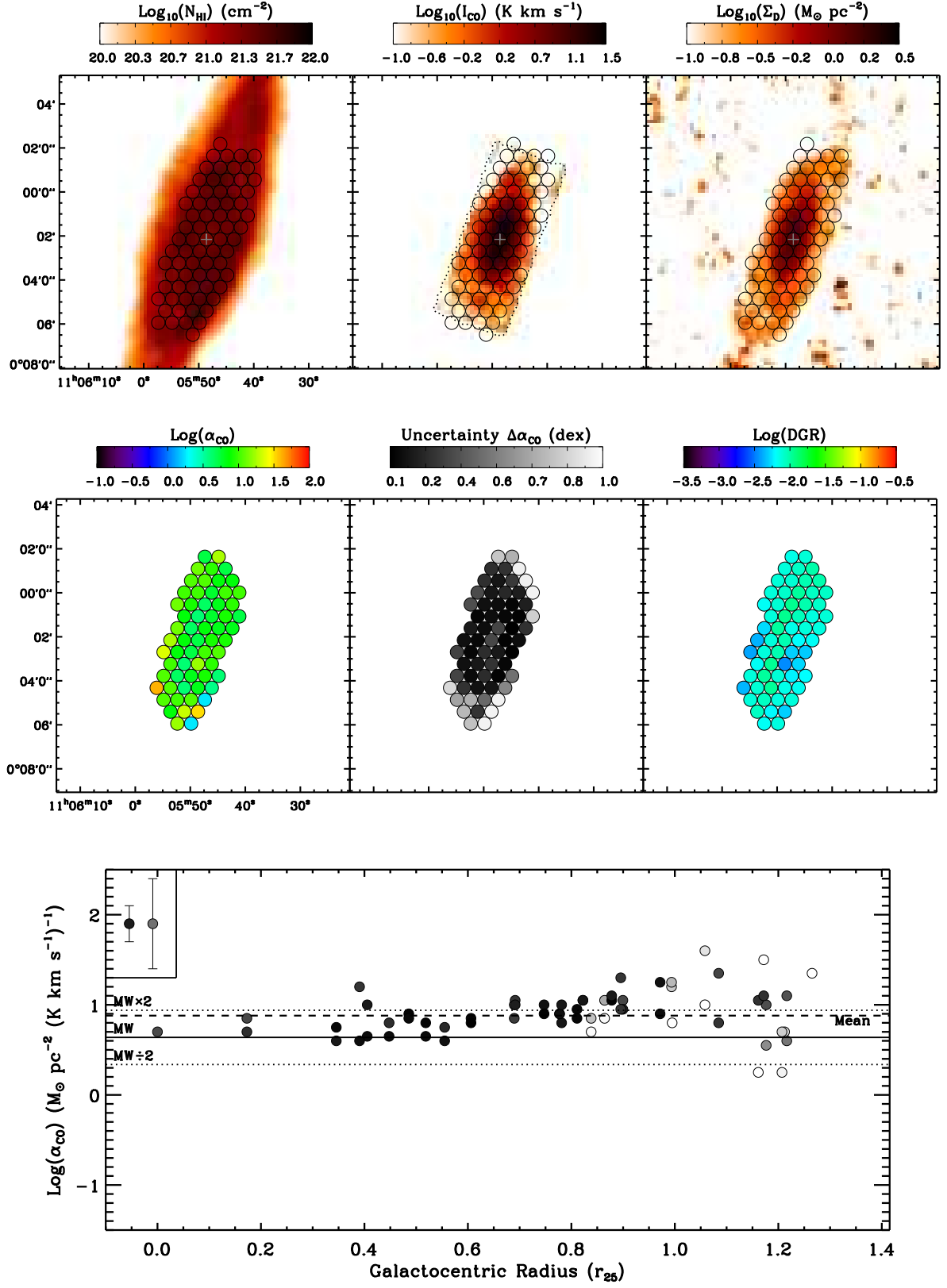


Figure 30. Results for NGC 3521.

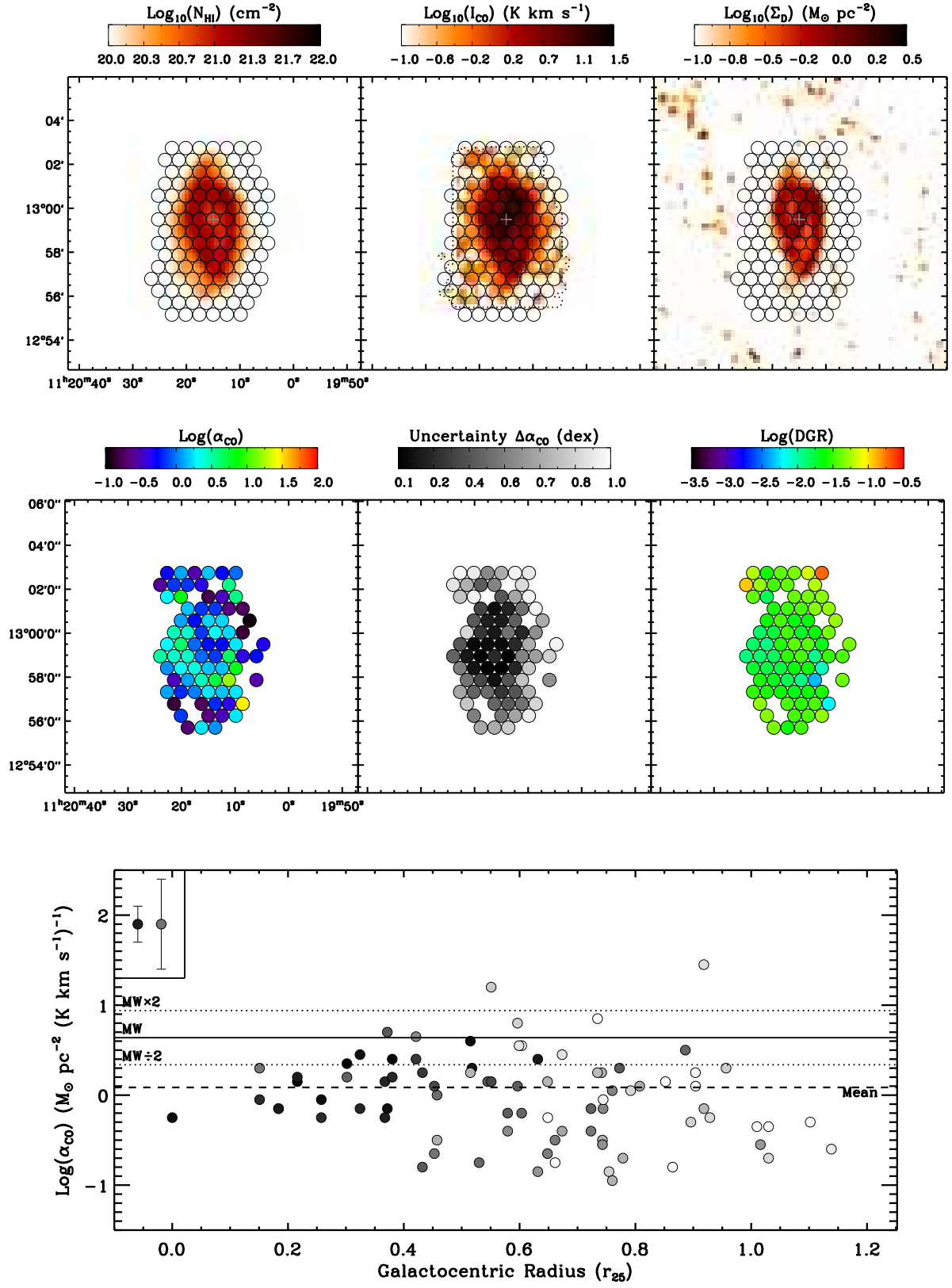


Figure 31. Results for NGC 3627.

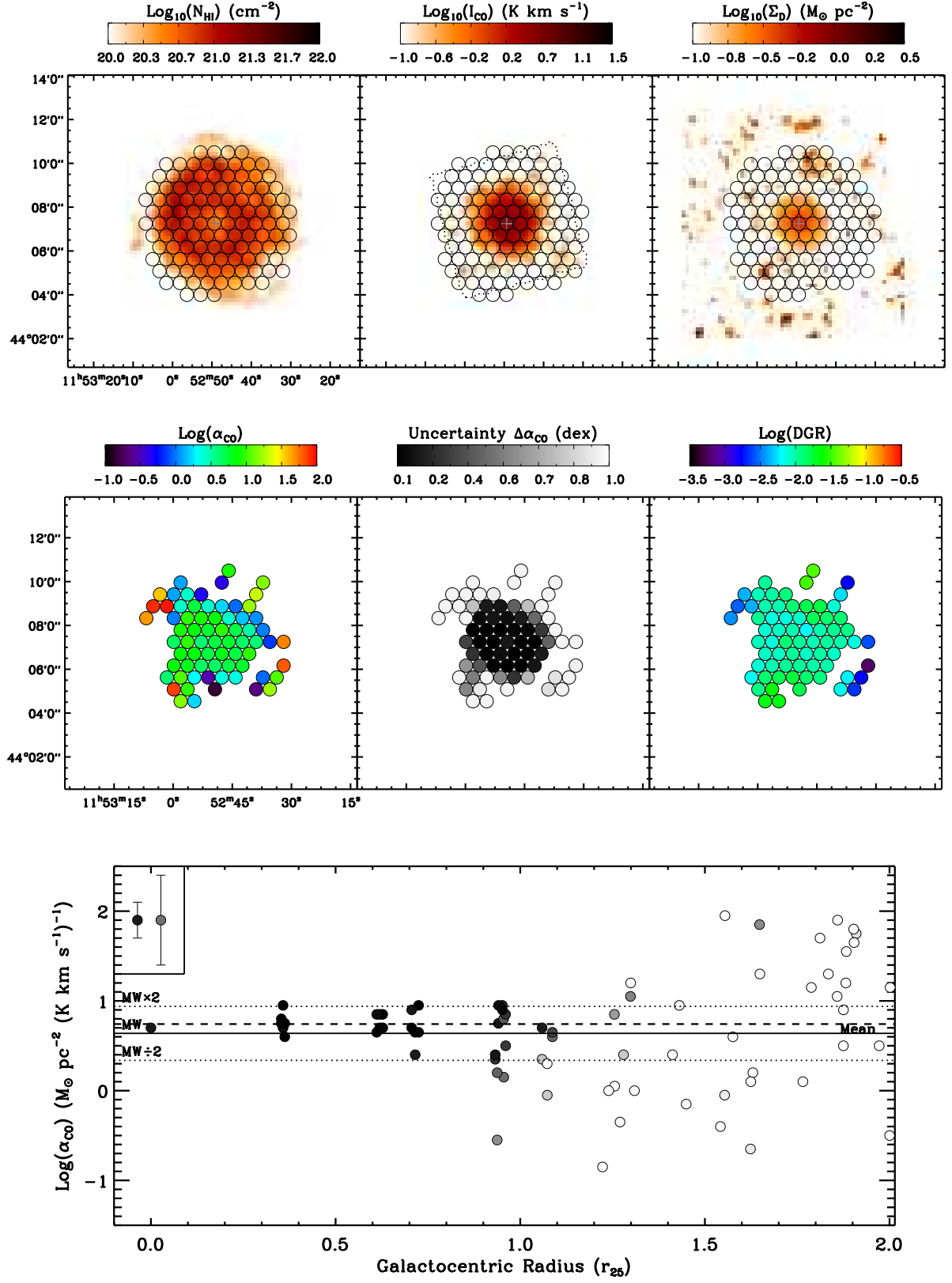


Figure 32. Results for NGC 3938.

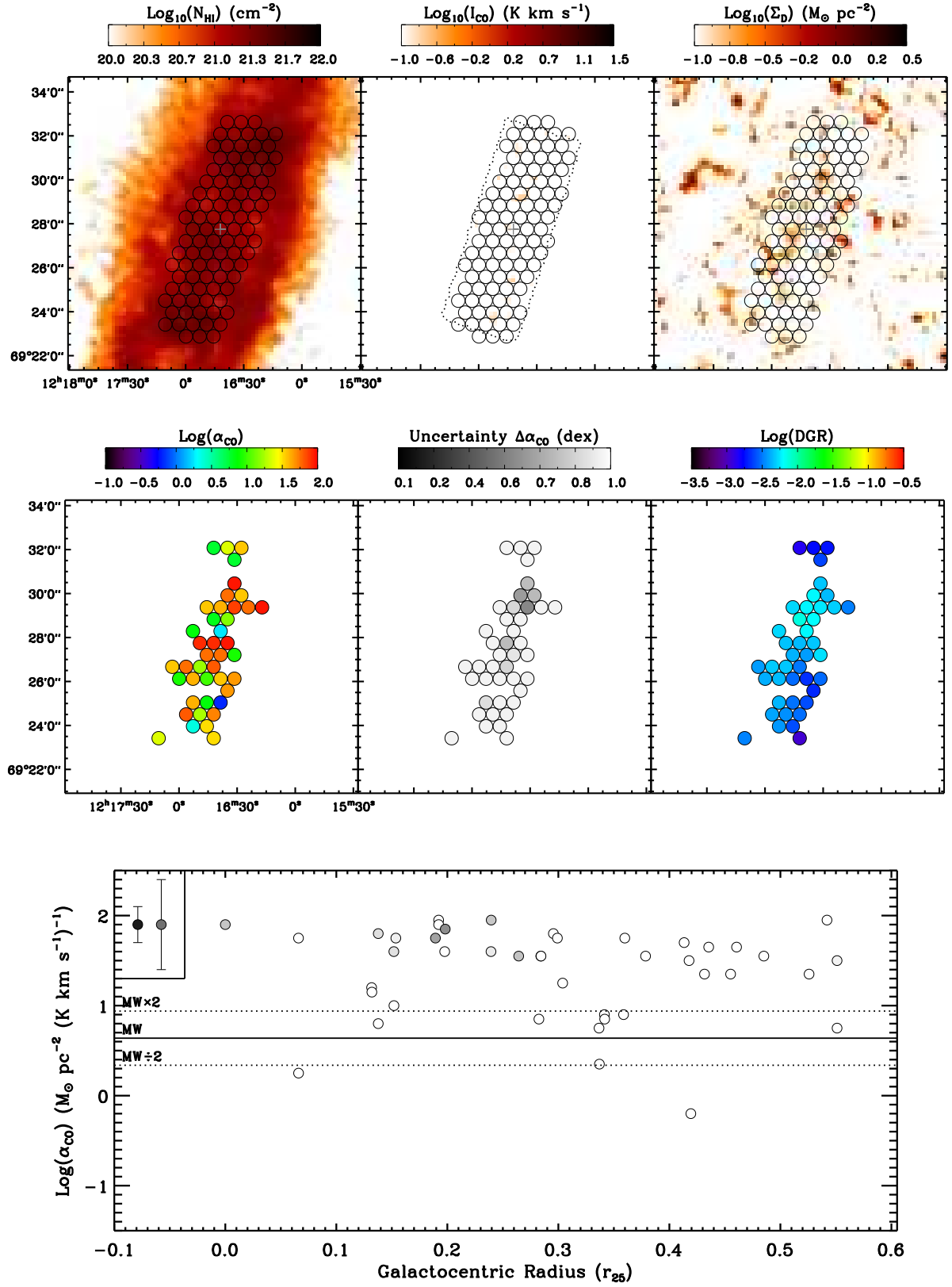


Figure 33. Results for NGC 4236.

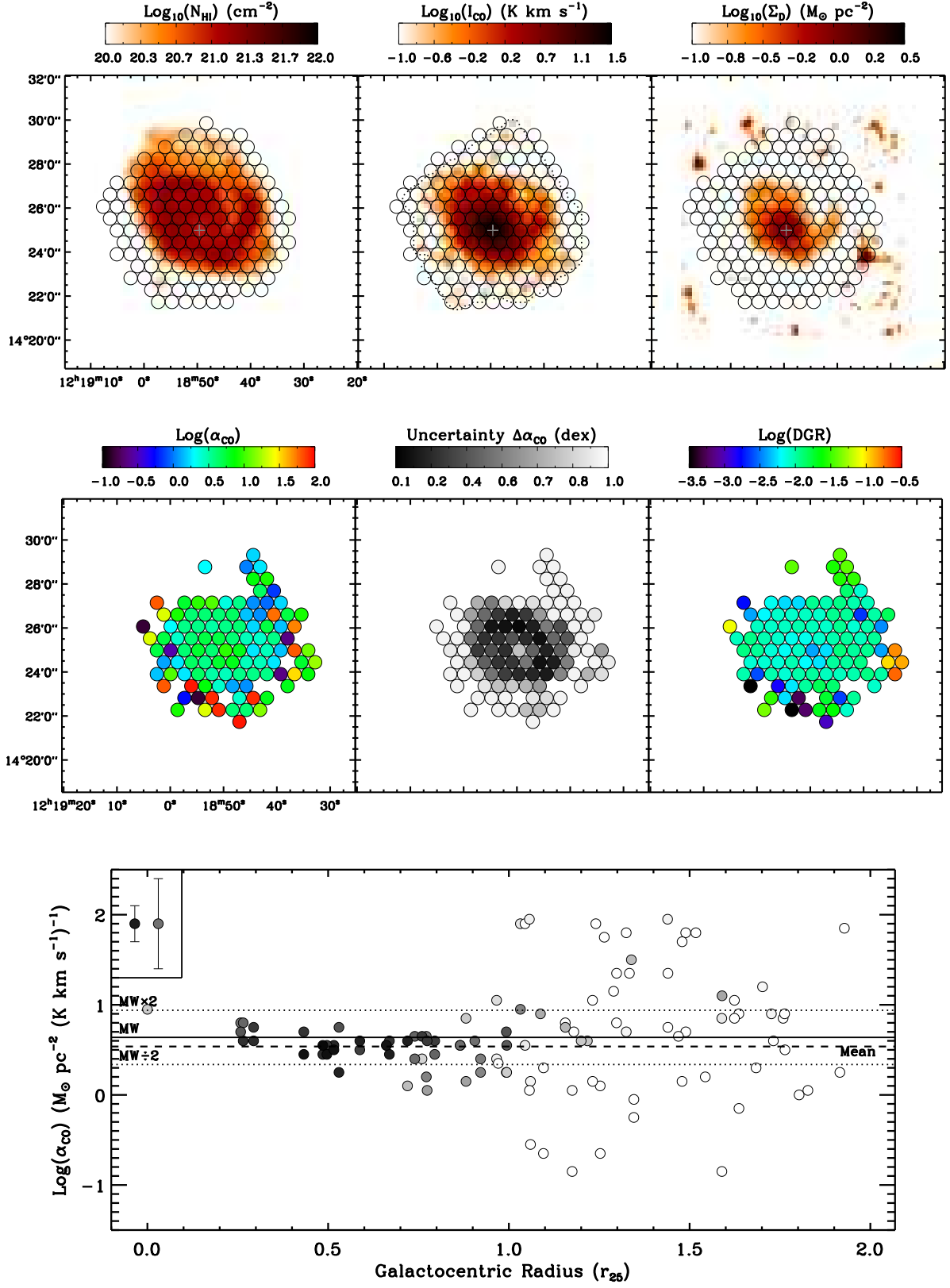


Figure 34. Results for NGC 4254.

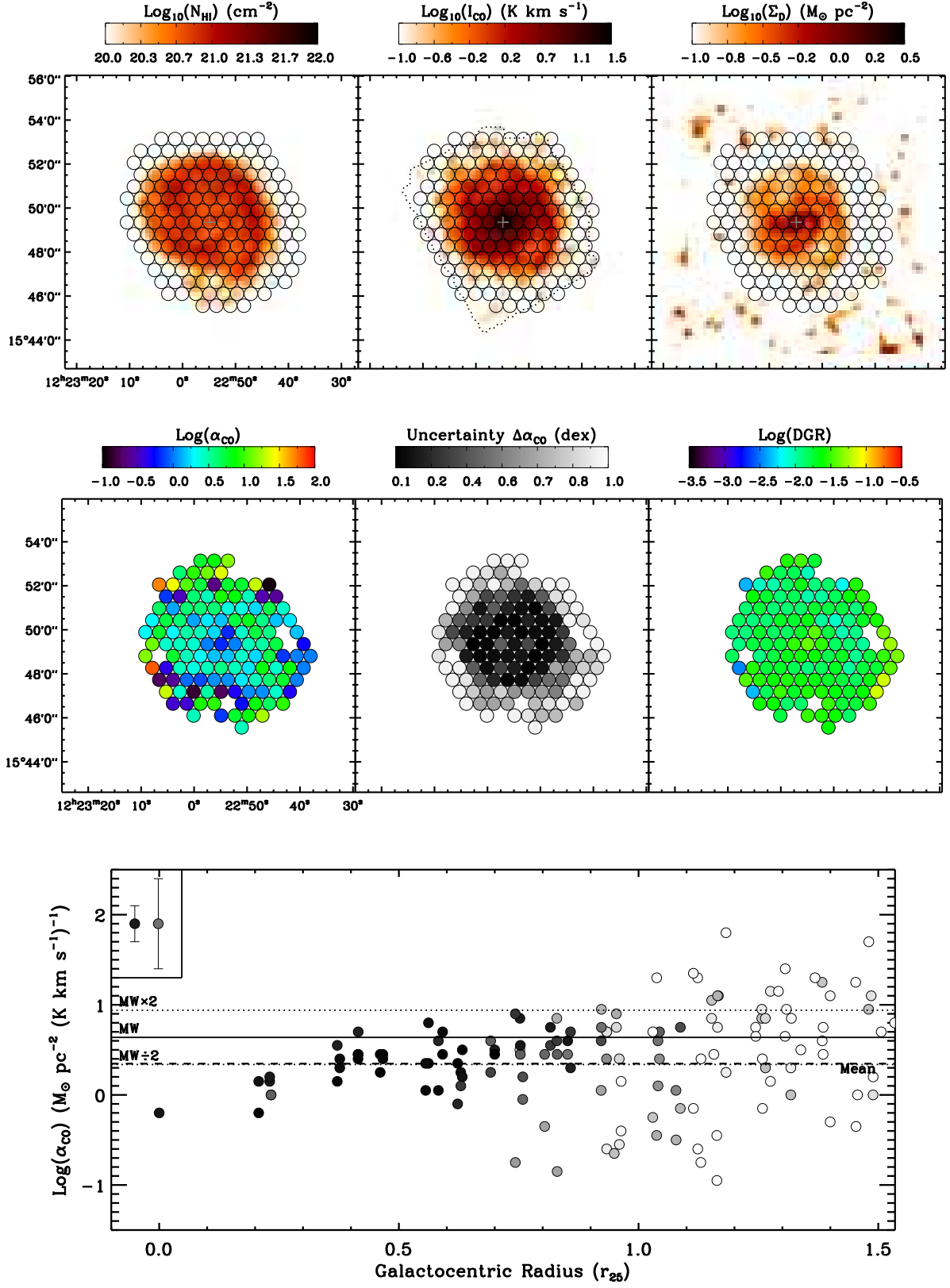


Figure 35. Results for NGC 4321.

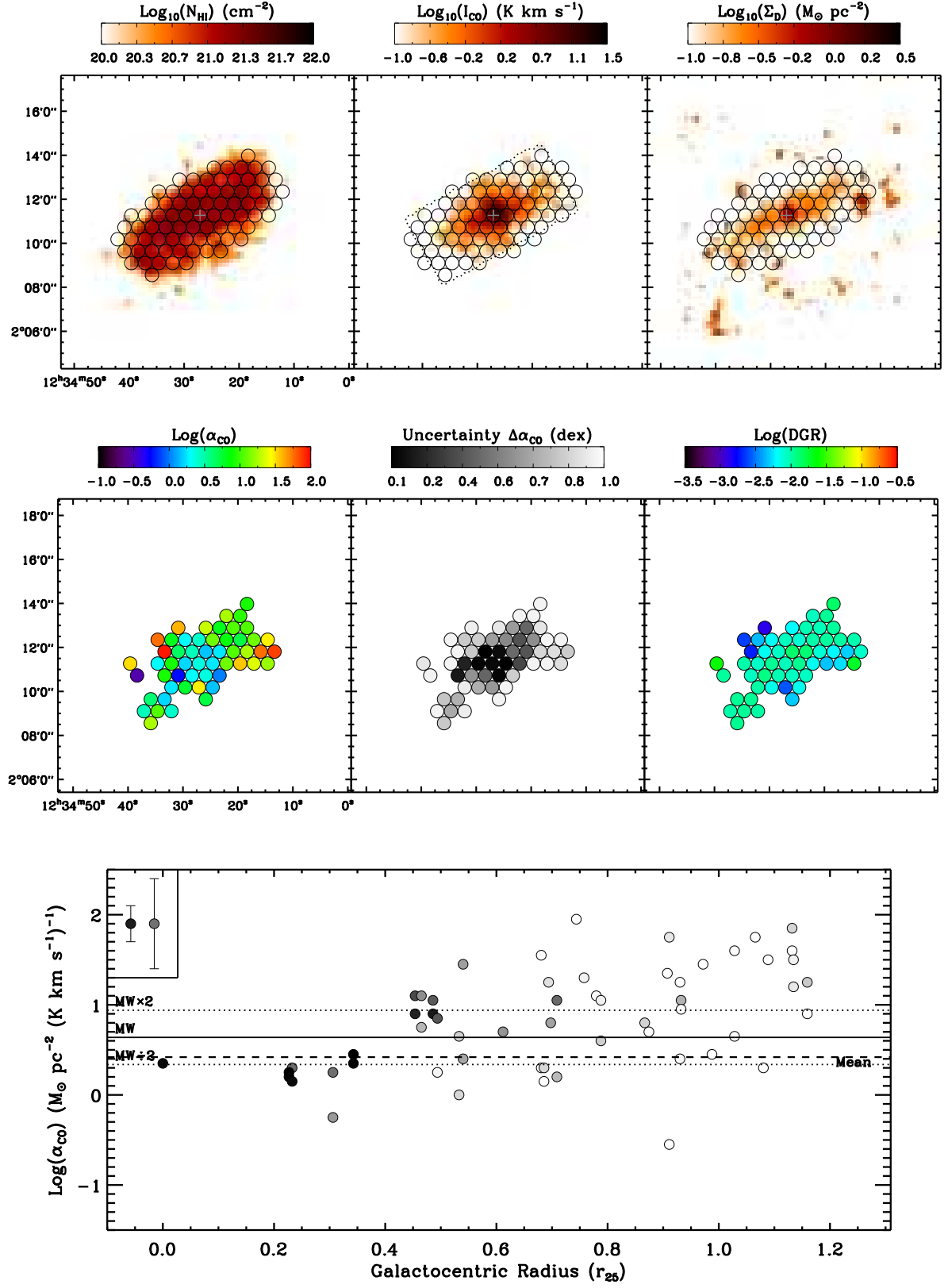


Figure 36. Results for NGC 4536.



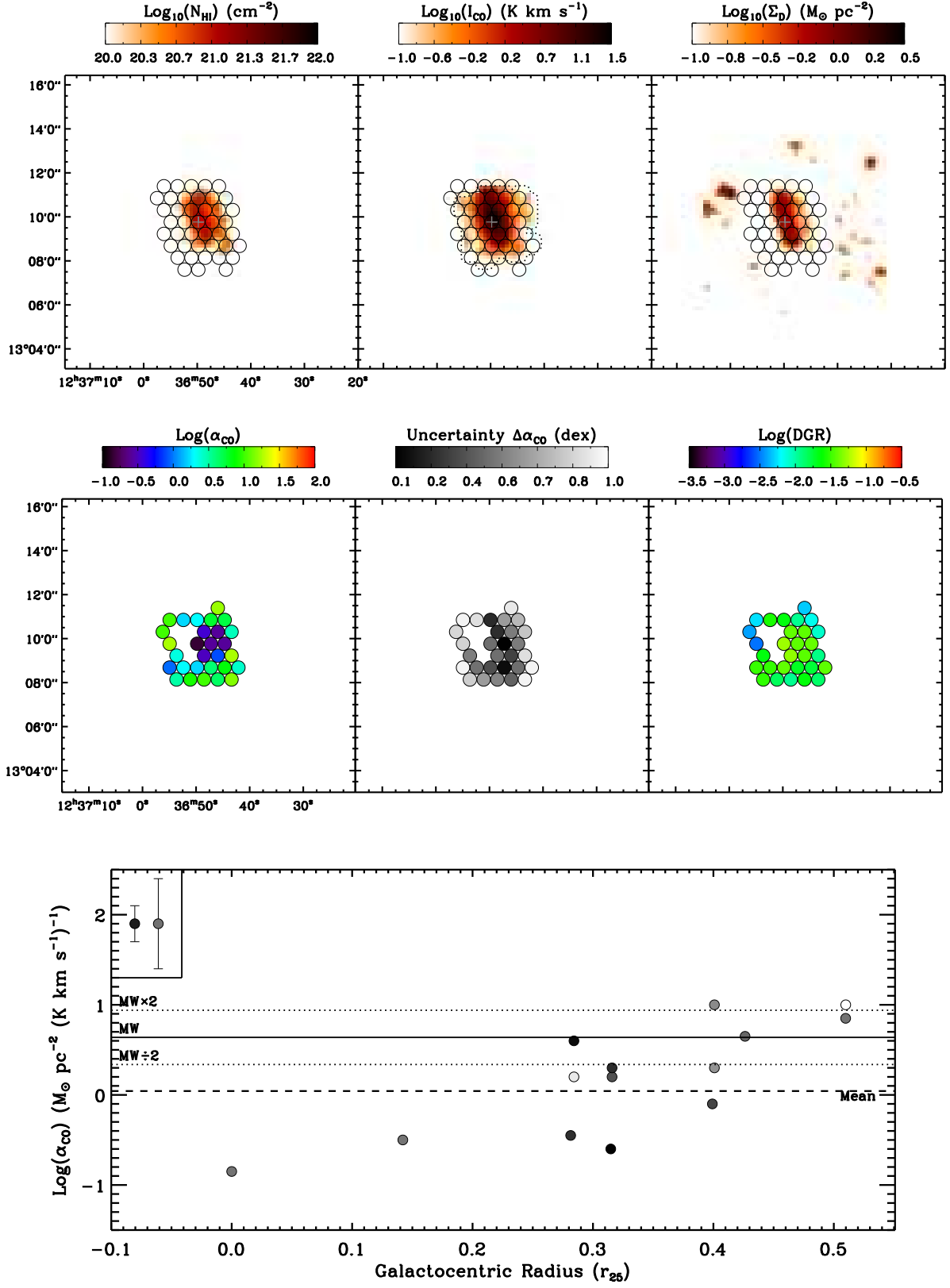


Figure 37. Results for NGC 4569.

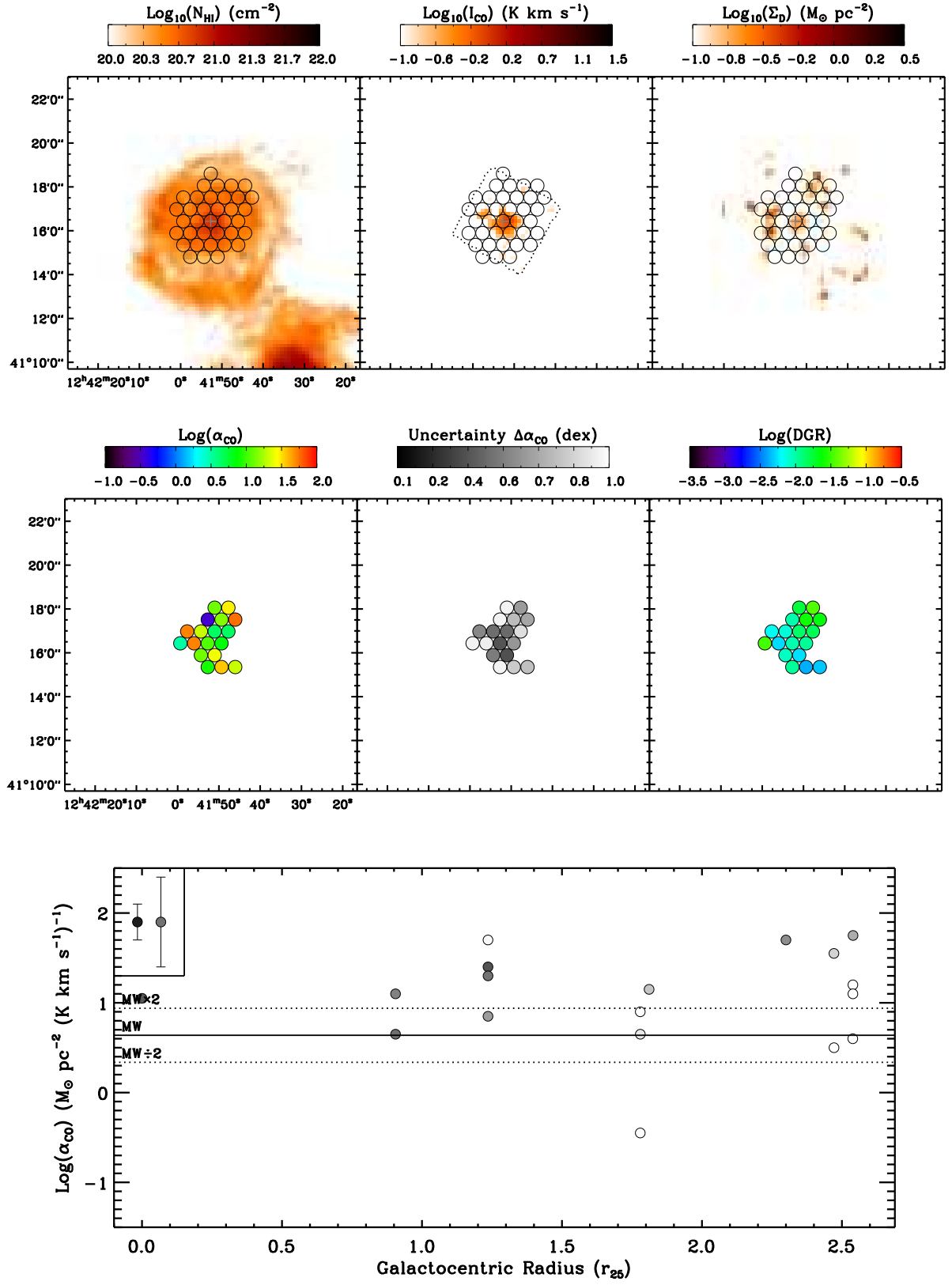


Figure 38. Results for NGC 4625.

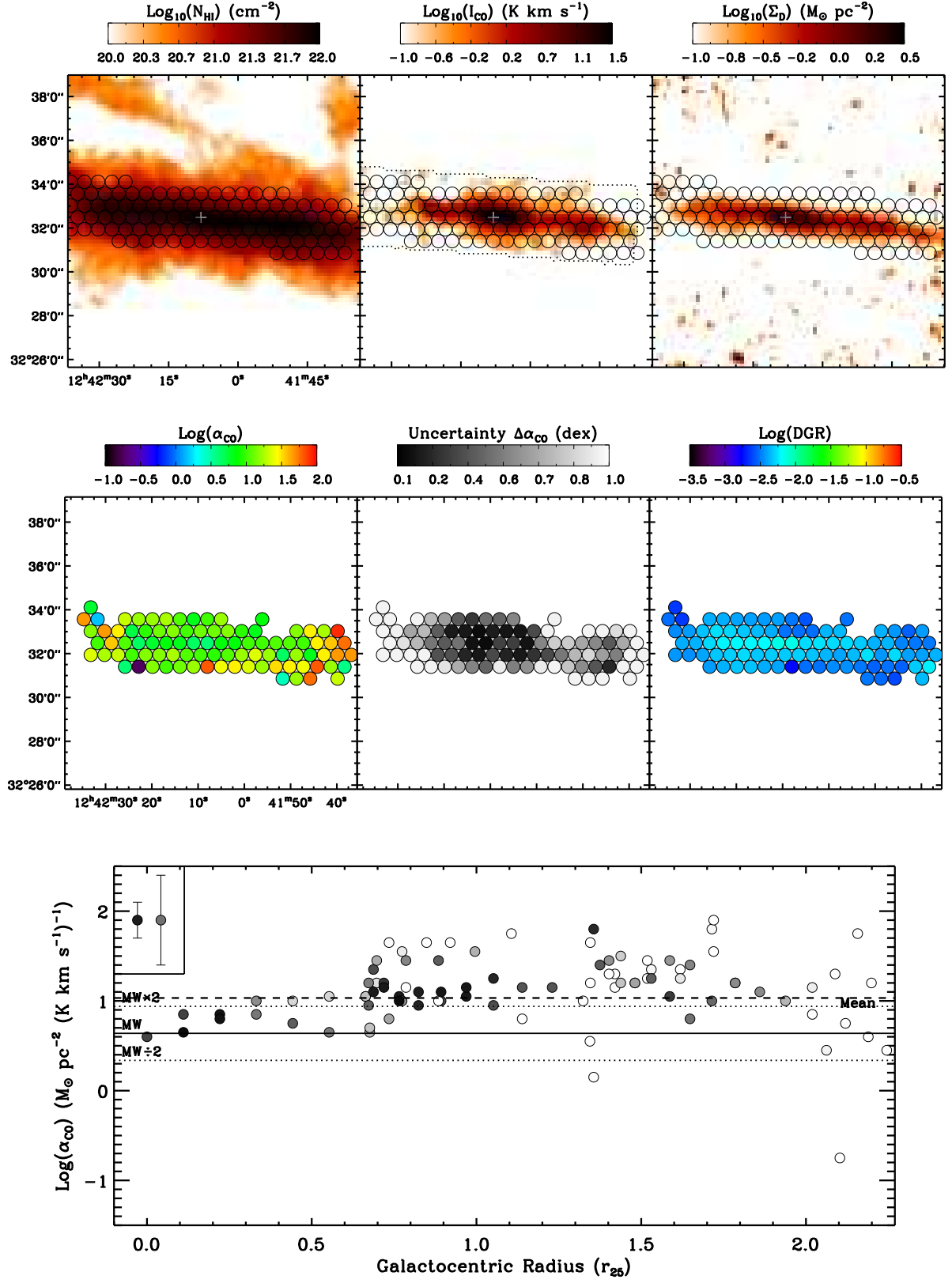


Figure 39. Results for NGC 4631.

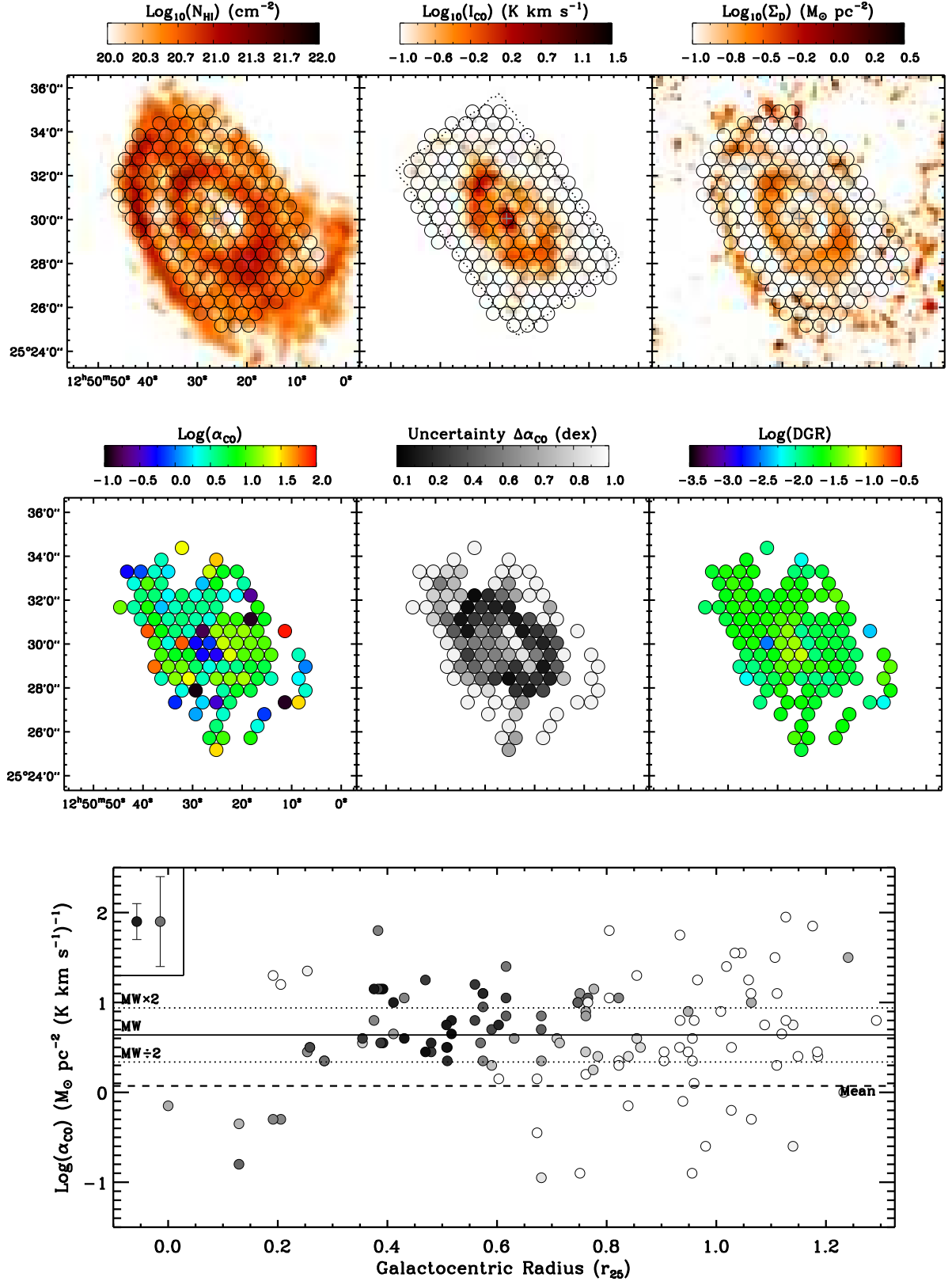


Figure 40. Results for NGC 4725.

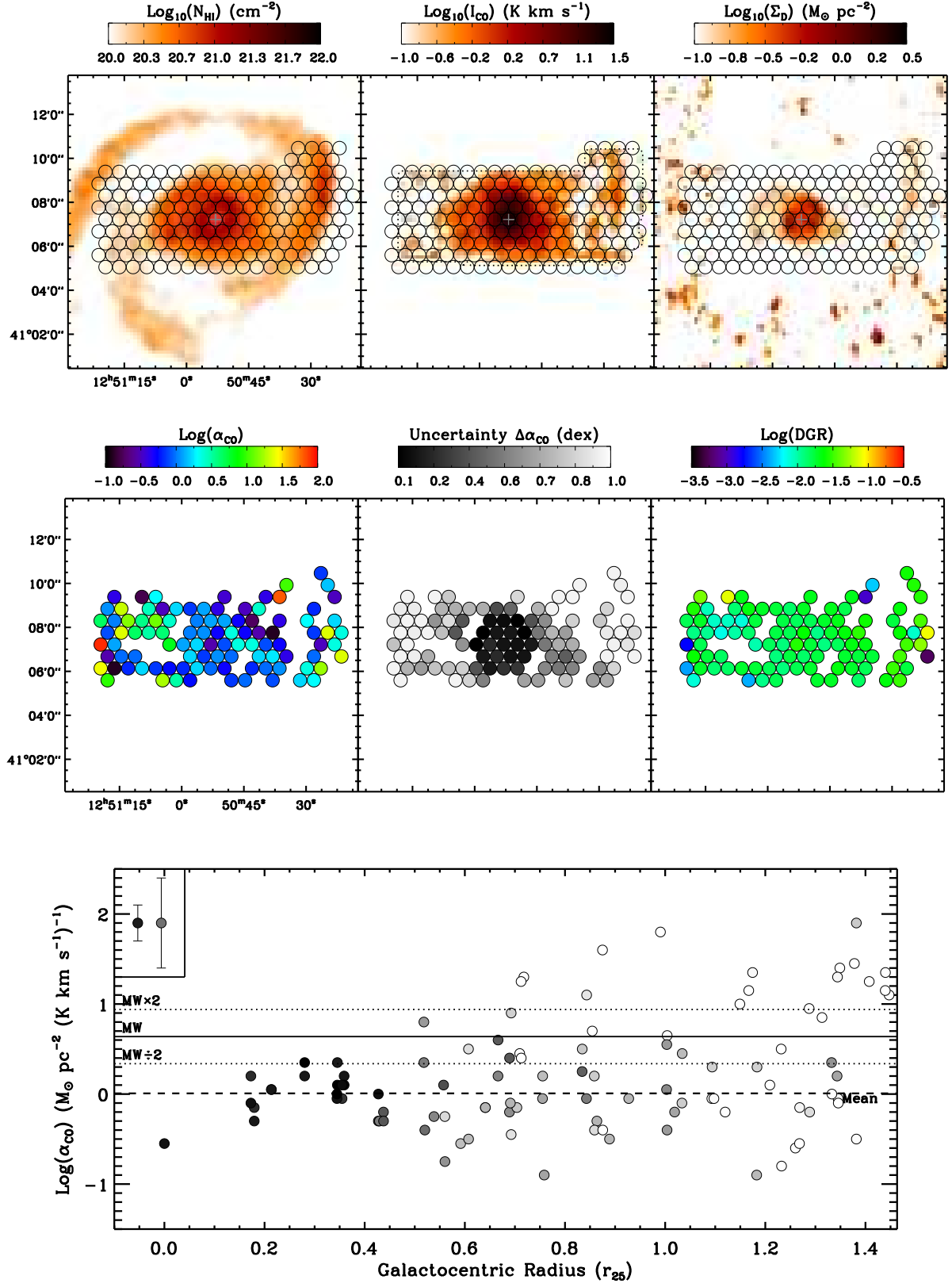


Figure 41. Results for NGC 4736.

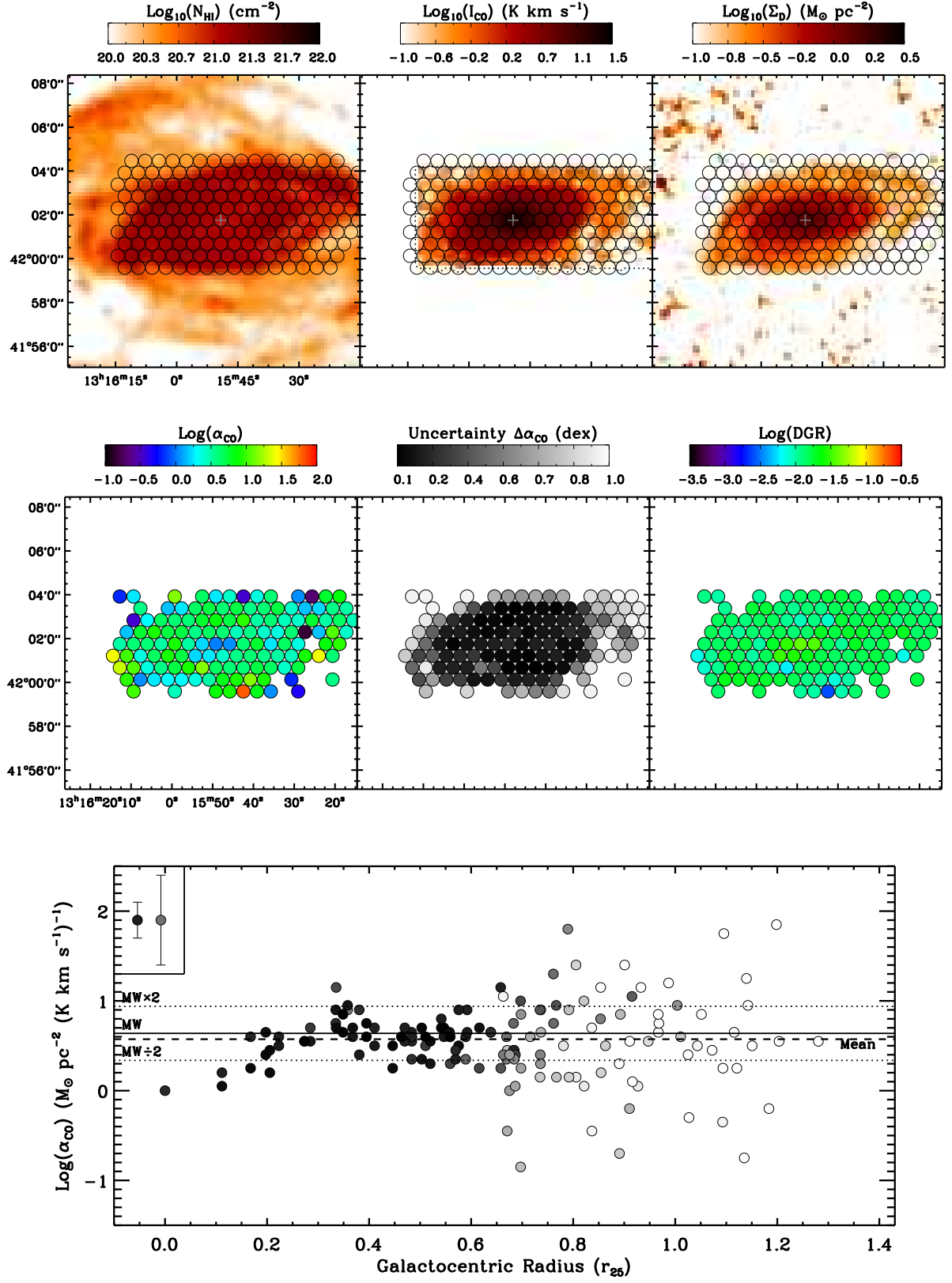


Figure 42. Results for NGC 5055.

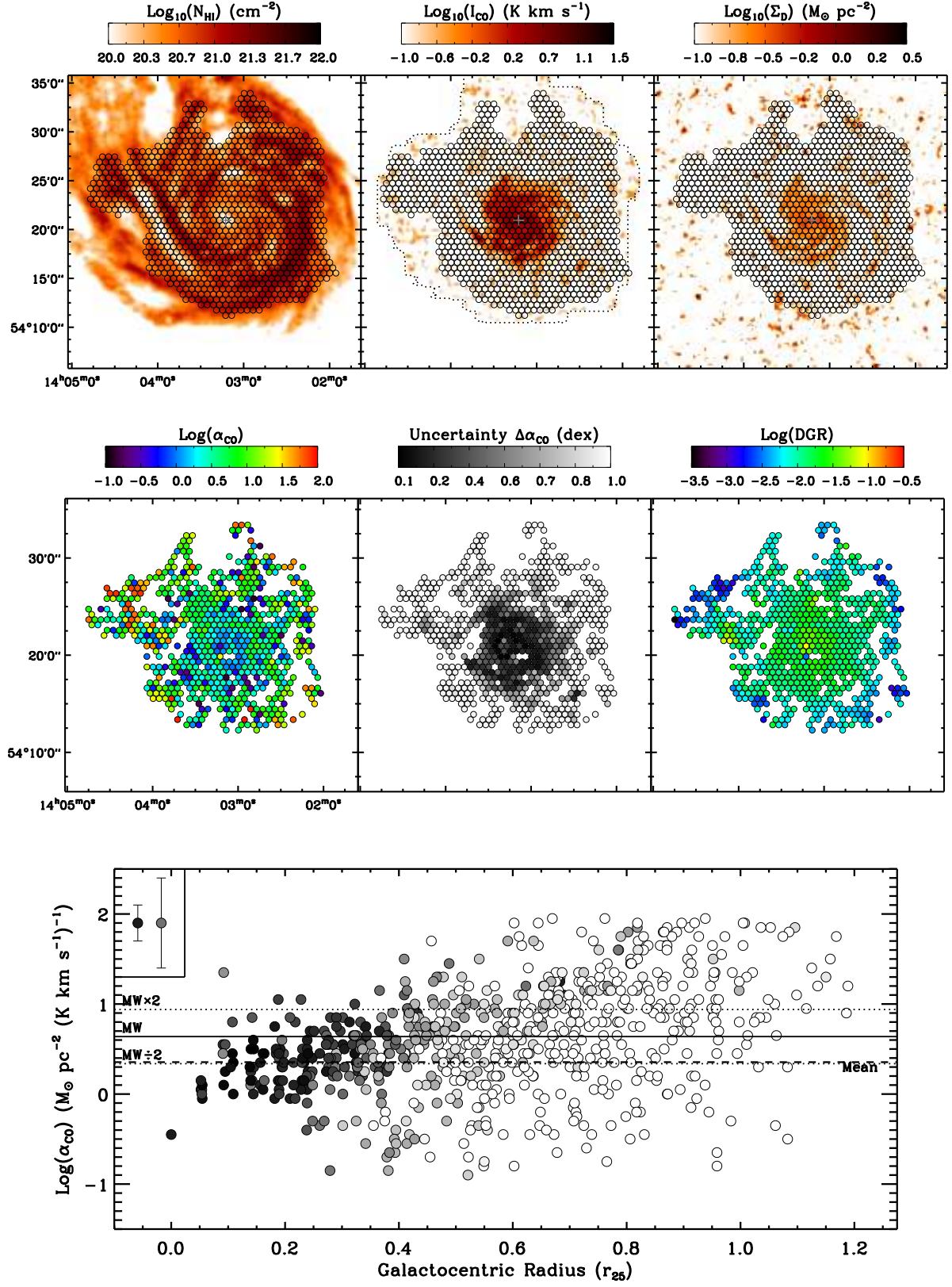


Figure 43. Results for NGC 5457.



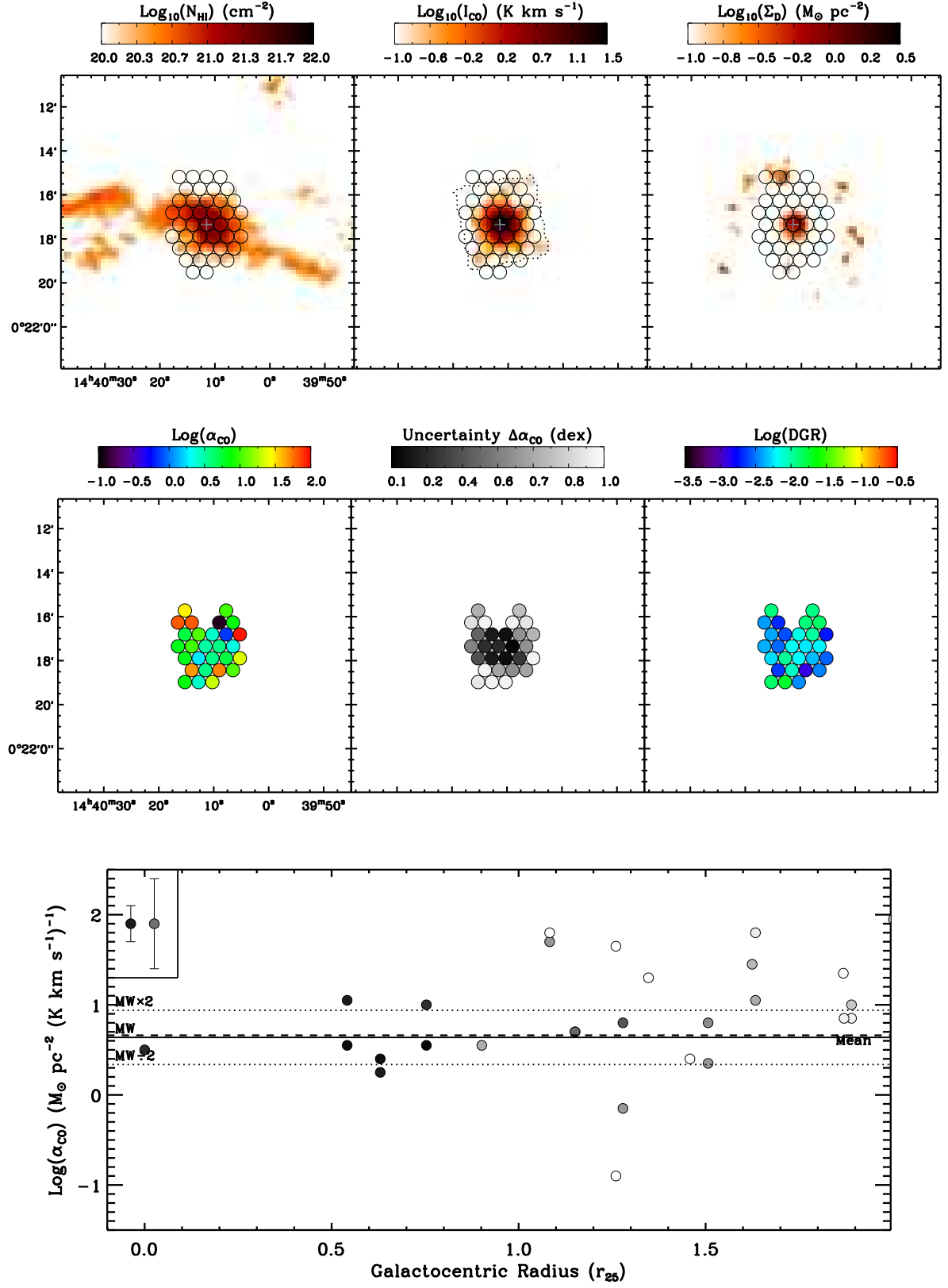


Figure 44. Results for NGC 5713.



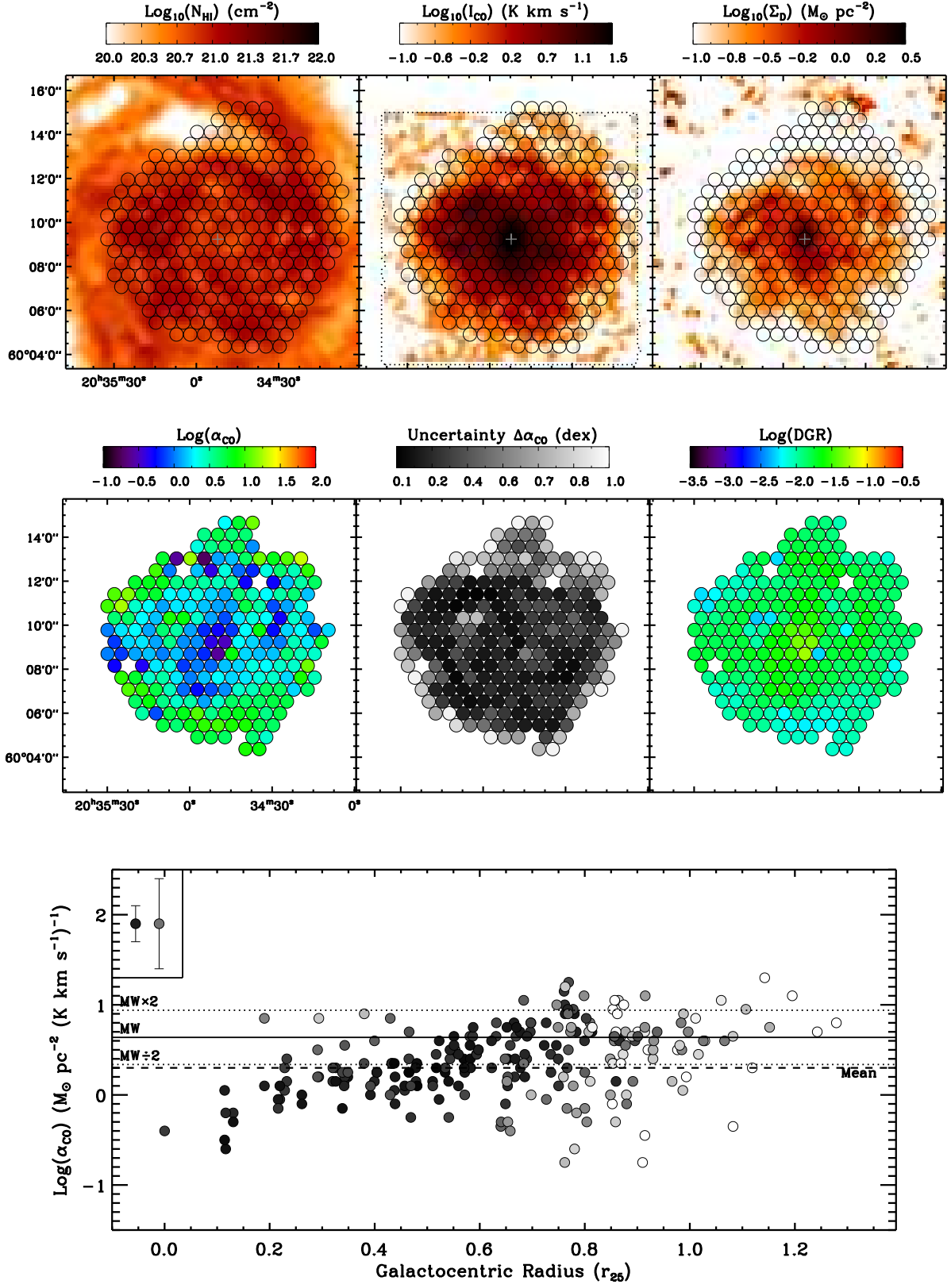


Figure 45. Results for NGC 6946.

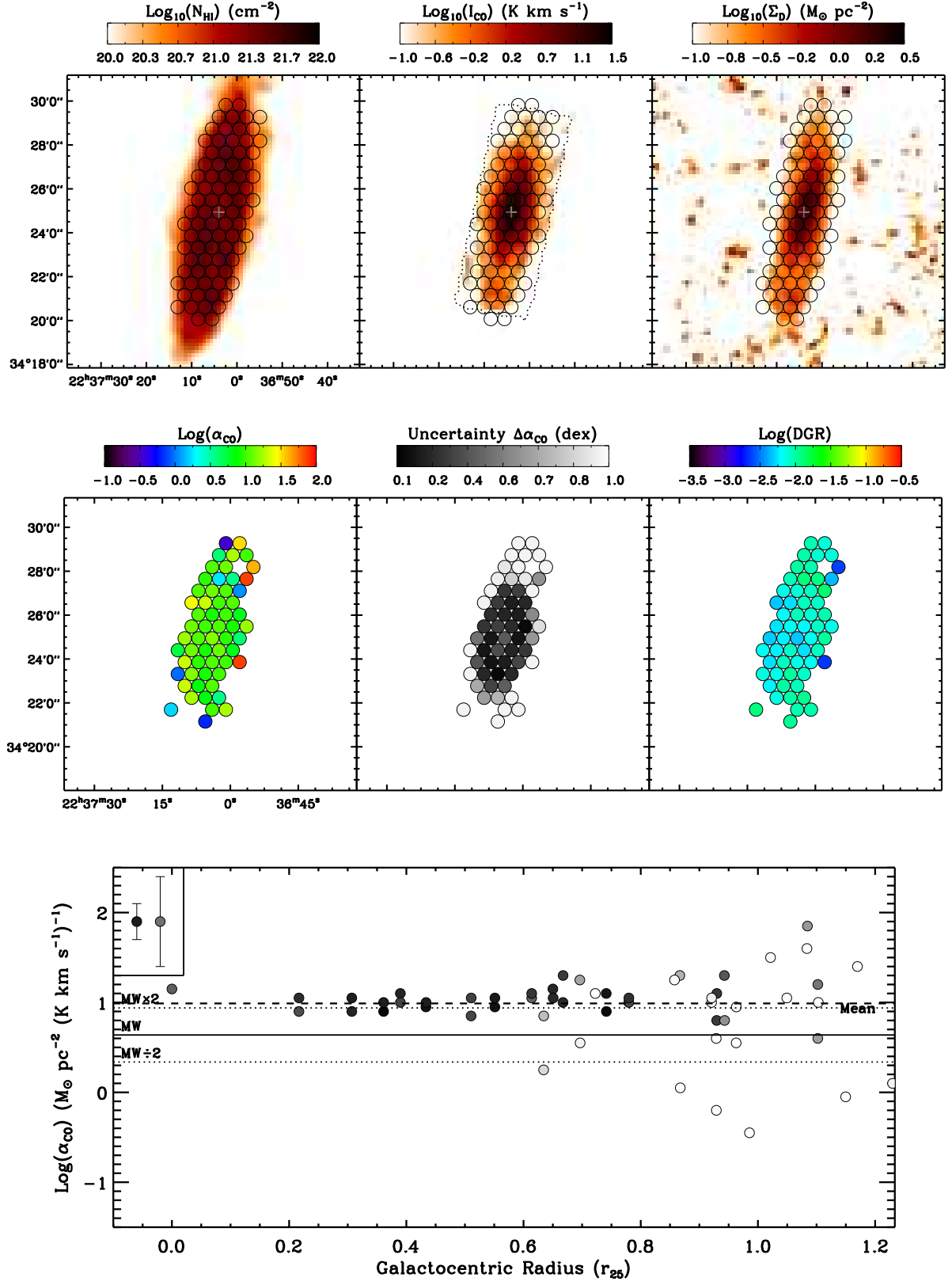


Figure 46. Results for NGC 7331.